Eucalypts as a genus for short rotation forestry in Great Britain

Andrew Dunbar Leslie

A thesis submitted for the degree of Doctor of Philosophy

Supervisors: Professor Maurizio Mencuccini
Dr Mike Perks

University of Edinburgh

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Declaration

I can confirm that I have composed the thesis and that the content is all my own work. Also the work has not been submitted for any other degree or professional qualification.

Andrew Leslie

Andrew Leslie

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I have been fortunate to have had the support of many people during the research for and the prepaprtion of this thesis. I have acknowledged the assistance of individuals associated with each study in the thesis but would also and in particular like to thank my wife and family for their considerable support during the six years of my studying. I would also acknowledge the crucial role of my supervisors, Professor Maurizio Mencuccini and Dr Mike Perks in guiding me through my studies with their expert input and timely advice.

Abstract

The study focused on four research objectives:

1. To identify the species and provenances of eucalypts most suitable for biomass production in Great Britain.
2. To compare growth of eucalypts with other promising short rotation forestry genera.
3. To develop volume and biomass functions for E. gunnii.
4. To estimate yields and patterns of growth for E. gunnii.

Searches on CAB abstracts and World of Science showed that there was limited research conducted on eucalypts in the UK. This research provides an original contribution to knowledge through; a long term assessment of the performance of species of cold tolerant eucalypts across a range of sites, identification of the basis for the rapid growth of eucalypts in comparison with trees from other genera, identification of the best fit function to describe stem form in E.gunnii and a characterisation of the pattern of growth in this species.

The thesis provides an account of the long history of eucalypts in the UK, the first record of a eucalypt being planted in Britain probably being Eucalyptus obliqua in the late 1700s (Aiton 1789). A review is then provided of the experience and constraints to growing nine eucalypt species in the UK and their potential for short rotation forestry are described. The rapid growth of eucalypts makes them well suited to short rotation forestry, but there are considerable risks from frosts and extreme winters.

Results from a trial established in Cumbria, north west England are described. Survival and growth was compared between E.gunnii, E. nitens and native or naturalised species, identified by Hardcastle (2006) as having potential for short rotation forestry. The rapid rate of growth of E. gunnii was attributed to a combination of large leaf area, a long period of growth during the year and a high specific leaf area. There was 99% mortality of E. nitens at the trial over winter, preventing comparison with other species. At the same trial and assessment was made of frost damage during the winter of 2009-2010, which proved to be the coldest for thirty years (Met Office 2010). E. gunnii was found to be more cold-tolerant than E. nitens, with 35% of the former surviving the winter and less than 1% of the latter. Larger trees were damaged more so than smaller trees reinforcing the argument for good silviculture to promote rapid, early growth.

The study on stem form and growth of E. gunnii represents the first in the UK. Volume, height and dbh of a total of 636 trees, measured by felling, optical dendrometer and terrestrial laser scanner were used to test the goodness of fit of a volume function developed in France by AFOCEL and is South America by Shell Oil. The AFOCEL function was found to predict volume with less bias and be suitable for all but the smallest trees. Characterisation of growth curves using mined historic data indicated yields of 16 m^3 ha^{-1} y^{-1} or approximately 8 t ha^{-1} y^{-1} at 20 years old. In contrast, growth curves derived from stem analysis of nine trees from Chiddingfold (south east England) and Glenbranter (central western Scotland) indicated lower yields at 7 m^3 ha^{-1} y^{-1} at age 28 years and 4.5 m^3 ha^{-1} y^{-1} at age 30 years respectively. Evidence from plantings elsewhere in the UK show that higher rates of growth are possible, but also that yields are often compromised by high mortality.

Chapter 1 Introduction

Two of the pressing needs for commercial forestry in the UK are identifying approaches that will meet the increasing demand for woody biomass, which has been driven by the Government's renewable energy and climate change policies (Carbon Trust 2005) and to create forests that are more resistant and resilient to climate change and to the action of pests and diseases (Park et al 2014).

1.1 Meeting demand for biomass

The EU has made ambitious commitments to reduce the level of green house gas emissions over the next ten years as part of their 20-20-20 programme. This aims to reduce emissions by 20%, increase generation of renewable energy by 20% and reduce energy use by 20% (European Commission 2013). In the UK there are two main aims of the Renewable Energy Strategy; to reduce emissions of carbon dioxide and to improve energy security. This is to be achieved through producing 15% of the energy in the UK through renewable means by 2020, which represents an increase of seven times the current contribution within a decade. The lead scenario generated within the Strategy suggests that 30% of electricity and 12% of heat could be provided through use of renewable sources of energy (DECC 2009). As a source of renewable energy, biomass has certain attractions, it can produce energy at times of peak demand, it can be produced in a carbon-lean way and tried and tested technology is available for its efficient conversion to usable energy. A review of the biomass sector in the UK by the Carbon Trust (2005) identified four main sources of biomass fuel; dry agricultural residues, forestry crops, waste wood and woody energy crops and using any of these for heat or generating electricity was considered to be a cost effective means of reducing carbon emissions. Converting biomass to biofuels was not investigated in the study due to extra cost of carbon saved due to lower conversion efficiencies. Combined heat and power plants across a wide range of scales were found to be cost-effective means of reducing carbon emissions.

If this demand for biomass is to be met domestically, the area under energy crops will need to increase dramatically. The UK Biomass Strategy (DECC 2009) predicts that 350,000 ha of perennial energy crops would be required by 2020, which is in contrast to the current 15,500 ha of SRC and Miscanthus (SAC 2009), which is estimated to have a maximum production of around 5,000 t y^{-1} (Carbon Trust 2005). The Carbon Trust (2005) in their analysis of the biomass sector assumed that an area of agricultural land similar to that formerly under set-aside would be available, amounting to around 680,000 ha. This area would enable 80TWh y^{-1} of energy to be produced from all woody biomass, including traditional forestry, waste wood and woody energy crops.

There are two main approaches to growing woody biomass crops for energy; short rotation coppice (SRC) and short rotation forestry (SRF). A summary of production practices, inputs and yields is shown in Table 1.1.

Table 1.1: Characteristics of SRC and SRF (modified from SAC 2009)

	SRC	**SRF**
Production practices	Established at high planting densities using willow cuttings which are harvested every 2-4 years	Established from transplants at lower planting densities and harvested every 8-12 years
Inputs	Pre-planting herbicide. N application in year 2 after cutting . Few additional inputs	Pre-planting herbicide. N application to reflect crop uptake and maintain crop vigour Few additional inputs
Yields	7-12 odt ha^{-1} y^{-1}	5-15 odt $ha^{-1}y^{-1}$ estimated – depending on species

SRC is currently adopted and SRF has mainly been established in research plantings. However, Ramsay, (2004) notes that SRF produces a biomass crop that is better suited as a fuel in that it produces:

- High density wood
- Wood with suitable chemical characteristics for combustion
- Wood with a low moisture content

And in addition it can:

- Be easily harvested
- Be harvested using conventional machinery
- Be capable of being harvested all year around

An ideal tree or ideotype for short rotation forestry should have the following characteristics, in addition to the wood properties described above:

- The ability to coppice (Dickman 2006, Hinchee et al 2009, Guidi et al 2013,), avoiding the costs of planting and also enhancing growth rates in the second and subsequent rotations.
- Fast growth and high biomass yield (Guidi et al 2013), with MAI peaking early.
- Producing straight stems; lowering harvesting, handling and transportation costs (Walker et al 2013)
- Rapid establishment and site capture as any delays due to weed competition or browsing will heavily impact on yields. This often means use of intensive silvicultural practices (Dickman 2006).
- Resistant to pests and diseases and extremes in climate, such as cold and drought.
- Reproductiive or other characteristics that limit the likelihood of invasiveness (Gordon et al 2011)
- Low negative impacts on the environment, such as soil nutrients and moisture (Ranney and Mann 1994).

A review (Hardcastle 2006) of the potential impacts was funded by the Forestry Commission due to concerns about the effects of SRF on the environment. As there was a lack of examples of SRF in Britain the study was largely a survey of expert opinion. Potential tree species for SRF were compared and conifers were dismissed due to resins in the wood and slow initial growth while some commonly planted broadleaves were rejected due to slow growth rates or being demanding in terms of site.

Whether the projected increase in dedicated perennial energy crops will materialize will depend partly on the price obtained from alternative crops and the level of government support. Recently high prices in grain and oilseed prices combined with a reduction in support (direct planting grants, Energy Aid payments, removal of set-aside) have decreased the attractiveness of woody energy crops. Further, current short-term leases of land for livestock rearing will also produce better returns with lower risk, although livestock rearing is currently in decline (SAC 2009). There are not just financial barriers to the adoption of woody energy crops, as their cultivation represents a long term commitment and uncertainties exist in predicing yields. Where biomass crops could be attractive is where index linked payments are provided (such as were proposed by Silvigen, a former supplier for the Drax power station), which provide a greater degree of price security than from producing grain or where there is a local market for heat (SAC 2009).

Demand for woody biomass continues to increase, driven by three government initiatives; the Renewable Obligation, launched in 2002 (UK Government undated a), the Renewable Heat Incentive, which was introduced in 2011 (UK Government undated b), and the Feed in Tariff, which was launched in 2010 (UK Government undated c). Recent revisions to Renewable Obligation Certificates (ROCs) (Box 1.1) have meant that electricity generated using dedicated biomass crops receive two ROCs per MWh compared with forest residues receiving one ROC (New Energy Focus 2008). Overall, it was estimated that up to £30 billion in support will be forthcoming between 2009 and 2020 to increase the contribution of renewables to the energy mix (DECC 2009). Further if a move towards a more carbon-lean approach to farming is to be encouraged, then growing SRF or SRC results in reduced carbon inputs compared with arable cropping, although it has similar inputs to livestock production on upland sites (SAC 2005).

Box 1.1: ROCs or "renewable obligation certificates" are certificates issued to generators of electricity for producing a MWh through renewable means. Electricity generators are required through the Renewable Obligation to generate an increasing amount of their electricity through renewable sources of energy. Each generator must produce a certain number of ROCs related to the amount of electricity they generate. Those that produce a surplus can trade their ROCs to a fund and be paid for them, while those that do not produce enough must purchase ROCs from the fund, creating a market value for renewable electricity (New Energy Focus 2008).

The Feed in Tariff is a payment made for electricity generated by renewable means, including through the burning of woody biomass and is funded through monies paid by consumers of energy. The Renewable Heat Incentive (UK Government undated b) operates in a similar way, paying producers of renewable heat, but funding is from the Treasury.

There has been insufficient supply of domestic woody biomass for electricity generation and an important imported source has been pellets produced from trees grown in the southern USA (Hammel 2013). This has however caused some concern because of the potential for overexploitation of forests (Carey Institute for Ecosystem Studies 2014, NDRC 2014). On 24 April 2014 an open letter was written from a group of over sixty distinguished scientists under the Carey Institute for Ecosystem Studies to the Secretary of State for Energy and Climate Change describing the considerable growth in exports of wood from the Southern USA and its potential negative impacts on forests in the southern states of the USA. In 2012 1.7 million tons of wood was exported for electricity generation, while in 2015 it is expected to reach 5.7 million tons (Carey Institute for Ecosystem Studies 2014). Stephenson and Mackay (2014) investigated the impact of sourcing woody biomass from the USA in a report for DECC in terms of greenhouse gas emissions. This investigated a number of scenarios and found that the benefits of using North American biomass, in terms of greenhouse gas mitigation was dependent on the source of woody biomass and assumptions on how it would be used. There were however scenarios that resulted in greenhouse gas emissions lower than 200 kilograms of CO_2 equivalent per MWh when fully accounting for changes due to land carbon stock changes. In contrast, some approaches produced emissions over long time periods of 40 to 100 years that were greater than buring coal. Another important issue however is the energy input associated with North American biomass which is higher in terms of energy carrier input per MWh delivered than other energy alternatives (Stephenson and Mackay 2014). These potential drawbacks of using North American biomass may focus resources on developing a larger domestic woody biomass resource in the UK.

1.2 Broadening the range of trees used in production forestry

There is a need to develop forests that are more resilient and resistant to biotic and abiotic stresses and better able to counter the effects of forecast changes to the climate (Park et al 2014). It is also to reduce the risk from catastrophic pest and pathogen damage. (Waring and O'Hara 2005). There has been an increase in the impact of pests and diseases on forest trees in this decade (Waring and O'Hara 2005). An increase in damage by red band needle blight (Dothistroma septosporum) has precluded the use of Corsican pine (Pinus nigra ssp. laricio) and more recently brought into question the future of Lodgepole pine (Pinus contorta) and Scots pine (Pinus sylvestris) as commercial species (Brown and Webber 2008). Furthermore the introduction of Phytophthora ramorum through the ornamental plant trade and its devastating impact on Japanese larch (Larix kaempferi) has to date killed millions of trees (Van Poucke et al 2012). Native trees have also been affected by introduced pathogens, such as Hymenoscyphus pseudoalbidus on ash (Fraxinus excelsior) (Woodward and Boa 2013), Phythophthora alni on alder (Alnus glutinosa) (Webber, Gibbs and Hendry 2014) and Phytophthora austrocedrae on juniper (Juniperus communis) (Green et al 2014).

Insect pests have been less damaging to date, but there are concerns that forecast warmer winters in the future will increase damage by the green spruce aphid (Elatobium abietum) on the main production species in Britain, sitka spruce (Picea sitchensis) (Broadmeadow et al 2003).

Threats to native trees include that to ash from the Emerald Ash borer (Agrilus planipennis), now in Russia, (Straw et al 2013), the Bronze Birch Borer (Agrilus anxius) which is capable of killing native birch (Betula spp) (European and Medierranean Plant Protection Agency undated) and Asian Longhorn Beetle (Anoplophora glabripennis) which will infest and kill a range of native hardwoods (Forestry Commission 2013).

An element of developing flexible portfolios of strategies to reduce risk will include broadening the range of tree species planted (Park et al 2014). Studies have been conducted on identifying alternative conifer species to those extensively used currently in production forestry in the UK (Wilson 2011). There have also been investigations of the potential of Mediterranean trees that could have a role in the warmer, drier parts of the UK (Wilson 2014). However there has been less work undertaken on minor broadleaved trees that have potential for production forestry in the future. A genus of broadleaved trees that may have potential for production forestry on specific sites in the UK is Eucalyptus.

1.3 Eucalyptus as a production genus

It is over 200 years ago that a tree in Australia was given the name Eucalyptus by Charles Louis L'Heritier de Brutelle (Turnbull 1991, Turnbull 1999). The genus Eucalyptus belongs to the family Myrtaceae, which is the eighth largest flowering plant family, with between 130 and 150 genera and over 5,650 species. Their distribution is mainly in the southern hemisphere (Grattapaglia et al 2012).

The genus Eucalyptus contains over 700 species (Brooker 2000). Of these some have a wide, but discontinuous distribution while others occupy specialised niches. Many species exhibit high levels of genetic variation, refelected by morphological variation within local populations and the presence of distinct ecotypes across environmental clines (Florence 2004). In the most recent revision of the taxonomy Brooker (2000) divided the genus into seven main subgenera; Angophora, Corymbia, Blakella, Eudesmia, Symphyomyrtus, Minutifructa and Eucalyptus. In addition, the genus includes six monotypic subgenera: Acerosa, Cruciformes, Alveolata, Cuboidea, Idiogenes and Primitiva. The opportunities for hybridisation between species depends on the closeness of their relatedness, with it being impossible between species in different subgenera (Florence 2004).

Most eucalypts are endemic to Australia, but two species, Eucalyptus deglupta and Eucalyptus urophylla are found exclusively outside Australia (Pryor 1976, FAO 1979). All eucalypts are found to to the west of Wallace's line making them part of the Austro-Malayan flora (FAO 1979) and their distribution covers a wide range of latitude, from 7^{o}N to 43^{o}39'S and a considerable variety of climatic zones (FAO 1979). They are found naturally from sea level to altitudes of 1,800 m (Kelly 1993 in Campinhos 1999) and this diversity of habitats has resulted in eucalypts being represented by growth forms from small shrubs to single stemmed trees of over 90 m in height and 6 m in diameter (Kelly 1993 in Campinhos 1999). However most are forest trees of between 30m to 50m in height or woodland trees of between 10 to 25 m in height. Between 30 and 40 species have adopted the mallee growth form, where several stems arise from a single underground woody stock (Pryor 1976).

Eucalypts are now one of the main genera used in production forestry; in 1991 there were approximately 8 million ha of plantations (Turnbull 1991). An FAO study conducted in 2005 (Del Lungo et al 2006) collected data on 34 selected countries, representing over 90% of the global total of plantation forest area and the total area of eucalypt plantation in these countries was estimated at just under 12 million ha, and the same data was used to produce a global estimate of 13.8 million ha (Carle and Holmgren 2009). By 2008 the global area had increased to 20 million ha of eucalypt plantations, with over half the area being found in three countries; Brazil, China and India (GIT Forestry 2009). In a study undertaken for the Forest Stewardship Council in 2012 the area under eucaypts was estimated to be 26% of the global industrial forest plantation total (Indufor 2012) (Figure 1.1). The extent of fast growing plantations is likely to continue to increase with predictions being that it will double worldwide by 2050 (Indufor 2012). Of the seven hundred species of eucalypts (Poke et al 2005), over 90% of plantations comprise nine species; Eucalyptus camaldulensis, Eucalyptus grandis, Eucalyptus tereticornis, Eucalyptus globulus, Eucalyptus nitens, Eucalyptus urophylla, Eucalyptus saligna, Eucalyptus dunnii, and Eucalyptus pellita (Stanturf et al 2013).

Some species exhibit attractive characteristics for production forestry; rapid growth, wide site tolerances, ease of management through coppicing and other characteristics and provision of valuable wood and non-wood products. They also produce orthodox seeds, that can easily be stored and their seedlings are relatively straightforward to propagate (Turnbull 1999). However, most species of eucalypt inhabit tropical and sub-tropical climates and are not suited to the maritime, temperate climates like the UK (FAO 1979, Evans 1980a, Booth 2013). Despite this, there has been a long history of eucalypts in Britain, and evidence exists of the suitability of some species and provenances to the climate of specific parts of Britain's climate (Evans 1986). A history of eucalypts in Britain is described in Section 2.1

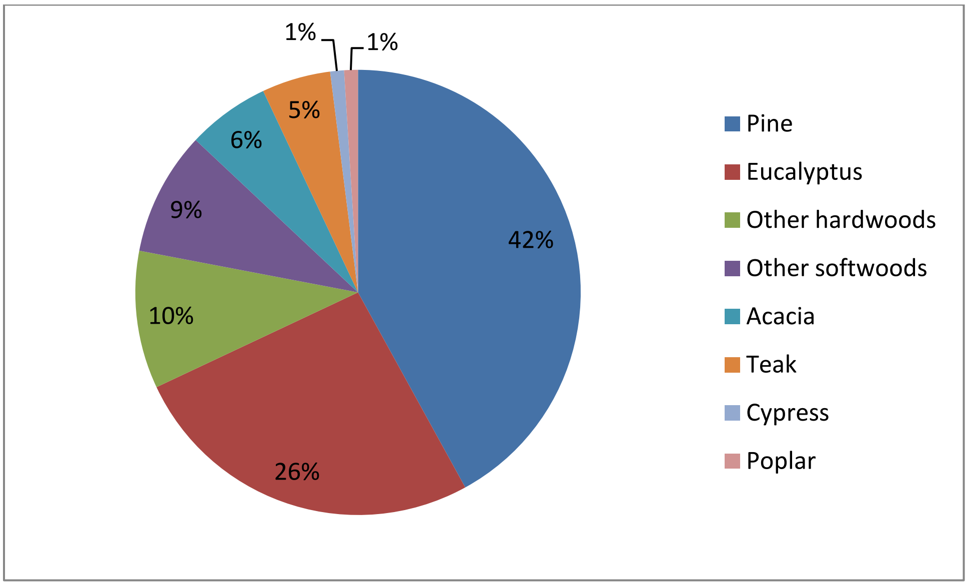

Figure 1.1 Industrial forest plantations by species, the total being 54.3 million ha (Indufor 2012)

High potential productivity is one of the characteristics that makes eucalypts attractive as producers of wood fibre, be it for solid wood products, energy or pulp. Improvements in productivity in eucalypt plantations have been very varied, with productivities of managed plantations varying from 10 m^3 ha^{-1} y^{-1} to over 90 m^3 ha^{-1} y^{-1} (Campinhos 1999). Eucalypts respond well to intensive silviculture and this characteristic is apparent in some plantations in Brazil; in 1990 the average productivity was 26 m^3 ha^{-1} y^{-1}, by 2012 the mean annual increment of plantations of eucalypts had increased to 40.7 m^3 ha^{-1} y^{-1} and there were stands that were growing at 100 m^3 ha^{-1} y^{-1}. It is predicted that by 2050 the average growth rates will have increased further to 56 m^3 ha^{-1} y^{-1} (Colodette et al 2014). Approaches taken to boost productivity have included the development of high-yielding disease-resistant clonal hybrids, intensive establishment and precise matching of clones to site (Campinhos 1999).

Eucalypts have the capacity to provide a wide range of services and products over a varied range of environments. They are grown in industrial plantations but also are established for other purposes, such as provision of subsistence products such as fuelwood and poles and are planted around fields and along roads. For example, in China alone there are estimated to be 600,000 ha of eucalypts planted along roads and waterways and beside dwellings (Wang 1991 in Turnbull 1999). The trees are used for poles, firewood, oils and tannins and honey production. These products have significantly enhanced the quality of life, including income of farmers (Zheng 1998 in Turnbull 1999). Increasing populations in many developing countries will create more demand for such non-industrial products in the near future.

Fast growing industrial plantations have been largely established in the tropics and subtropics or warmer areas of temperate regions, such as the southern USA (Sedjo 1999). These have provided a competitive economic return and while productive forest plantations in many countries began as government initiatives or with significant government support, more recently the expansion has been through private investment (Sejdo 1999). Turnbull (1999) described the large scale industrial forest plantations of eucalypts as a relatively recent phenomenon, largely coming into existence since the late 1960s. He also notes that it is the most rapidly expanding sector in global forestry, with most of these plantations being found in Brazil, South Africa, Spain and Portugal.

In 2008, almost 50% of hardwood pulp and approximately 20% of pulp was produced from eucalypt plantations. Hardwood pulp and in particular eucalypt pulp is energy efficient to produce in comparsion to that produced from conifers (Moore and Jopson 2008). Whilst historically the focus of industrial eucalypt plantations has been on producing pulpwood and fuelwood there is an increasing interest in growing eucalypts on longer rotations and with thinning and pruning to produce timber (Flynn 2003). The wood of plantation grown Eucalyptus grandis, once stained, has been substituted for tropical hardwoods such as mahogany and for other tropical timbers in producing high quality plywood (Flynn 2003).

As a source of woodfuel, eucalypts have had a long history, being used in many countries to augment supplies from native forests. They are well suited to this purpose, producing dense wood, rapidly and also being able to coppice. In countries with developed economies, Turnbull (1991) noted in 1991 that there may be potential in the longer term for using short rotation eucalypt as a source of energy but only when yields were high and there was a short distance to the power station. Since then policies directed at reducing atmospheric greenhouse gases have stimulated interest in and provided support to the use of wood as a fuel in developed nations. In terms of biomass for energy, the main advantages of using woody crops rather than herbaceous ones, such as Miscanthus, are higher calorific values, the production of less ash and a smaller likelihood of causing slagging and fouling when incinerated (Ryu et al 2006). Section 2.2 describes the potential for eucalypts as a source of wood fuel in the UK.

There are controversial aspects to the planting of eucalypts and these generally relate to impacts on soil erosion, soil nutrients, water yield and biodiversity (Poore and Fries 1985, Turnbull 1999). However, these potential impacts are largely mitigated by responsible forest management (Poore and Fries 1985). The wide tolerances of site condition and high potential reproductive rates of eucalpts, has raised concerns about their potential invasiveness (Stanturf et al 2013). Booth (2013) however notes that there are biological characteristics of eucalypts that limit their ability to colonise new environments. These include the limited dispersal of seed, its short length of viability, the requirement for seed to fall on bare soil and also the high light intensities needed for germination. Furthermore, it is likely that for many species of eucalypts, the periodic, extremely cold winters experienced in the UK will limit the natural colonisation (Section 4.2 provides a discussion of mechanisms for cold tolerance in eucalypts).

1.4 Extent of previous and contemporary research

Using two appropriate databases, a search of terms relevant to this study was made in May 2014. This highlighted the paucity of published material on eucalypts in Great Britain or the UK. Furthermore, the number of references found in these searches included some that were not relevant, such as a reference on 'New Britain', part of Papua New Guineau. These searches show (Table 1.2) that relatively little has been published on the topic of eucalypts in Great Britain or the United Kingdom and on the species that were the main focus of this research; E. gunnii, E. subcrenulata and E. pauciflora.

Table 1.2: Results of searches on the CAB Abstracts (1973-2014) and Web of Science (1926-2014) databases.

	CAB Abstracts		Web of Science	
Text	**Title**	**Keyword**	**Title**	**Topic**
Eucalyptus	12,038	28,127	7, 314	17,431
Eucalyptus + Britain	0	142	2	18
Eucalyptus + UK	2	140	5	112
Eucalyptus + short rotation	54	363	27	199
Eucalyptus + *gunnii*	56	221	35	115
Eucalyptus + *subcrenulata*	6	6	0	3
Eucalyptus + *pauciflora*	56	226	61	248

Of the publications that have been published since the 1950s there have been a number of other useful publications, building knowledge of eucalypts as a productive genus in the UK or Ireland (Appendix 1, Table A1.1 to Table A1.3). The most important however, is Evans' (1980a) article reviewing the species that had been introduced into Britain, with observations of their performance. This information was used by the Forestry Commission to establish a series of trials, early ones in 1981 and a latter series in 1985, which, in the light of the earlier trials focused on more cold tolerant species. The early results of the trials were reported in another article by Evans (1986). A publication by Purse and Richardson (2001) commented on the later results of some of the Forestry Commission trials and also provided useful information on the performance of eucalypts in some private trials. A summary of performance of species planted in trials from the 1930s to date in Ireland was summarised in Neilan and Thompson (2008). Results of those Forestry Commission trials that remain in reasonable condition have been presented in publications related to this study (Leslie, Mencuccini and Perks 2013, Leslie, Mencuccini and Perks 2014a).

1.5 Aims and objectives of the study

The overall aim of this study is:

To determine the potential role eucalypts have in the production of biomass through short-rotation forestry in Britain.

This will be achieved through the following four focused objectives that will guide the research and contents of six chapters that make up the dissertation. The objectives are as follows:

1. To identify the species and provenances of eucalypts most suitable for biomass production in Great Britain.
2. To compare growth of eucalypts with other promising SRF genera.
3. To develop volume and biomass functions for E. gunnii.
4. To estimate yields and patterns of growth for E. gunnii.

The approach used to meet each of these objectives is described in the Overview of Chapters section.

1.5 Justification of study

While SRF offers some potential as a system to provide a renewable source of energy, relatively little is known about the species that might best provide wood energy on an industrial scale in the UK and of the silviculture needed to maximize yields. Indeed, the first recommendation in Hardcastle's (2006) review was that:

"An active programme of research to increase the body of knowledge on SRF practices and on the growth rates and yields of biomass material that can be obtained in UK is required as a *matter of urgency"* (Hardcastle 2006 piii).

This study as part of its objectives will compare the yields of a number of potential SRF species. Estimates of yields are presented in Hardcastle's (2006) report and these showed that eucalypts were the most attractive genus, due to their high growth rates (Table 1.3). This is supported by the little growth data available for the genus in the UK, but it would appear that yields of 30-40 $m^3\ ha^{-1}\ y^{-1}$ are possible.

The attractiveness of eucalypt SRF has been further supported in the Read Report (Read et al 2009), which provided a review of the role of the UK forests in combating climate change. This included an economic analysis of several forestry options in terms of the cost to reduce emissions of CO_2, which is reproduced in Table 1.4. Of these it is mainly high yielding eucalypt SRF that is considered to have the lowest cost of reducing emissions.

Table 1.3 Estimates of yields from favoured SRF species (Hardcastle 2006)

Species	**Dry t ha^{-1} y^{-1}**	**Rotation (years)**	**Yield - Dry t ha^{-1}**	**Yield - Wet t ha^{-1}**
Ash	7.4	20	148	296
Sycamore	7.0	20	140	280
Poplar	5.6	14	78	157
Alder	5.0	20	100	200
Birch	5.0	20	100	200
E gunnii	**9.0**	12	108	216
E nitens	**15.0**	8	120	240
Nothofagus	11.8	12	142	283

This study will contribute to the small body of knowledge Eucalyptus in Britain and investigating little-known tree genera is important as there is a pressing need to broaden the range of trees available to forestry. The investigation of the performance of a range of eucalypt species in existing trials such as those established in 1981/82 by Forest Research (Evans 1986) would provide useful information and supports one of the research priorities identified in the Read report (Read et al 2009 p114) which recommended the:

"Trialing of species that may be suitable for the current and projected British climate."

Within the Read report (Read et al 2009 p114) there are two other research priorities that will be directly supported through the results of this study:

*"[To] improve knowledge of the role of fast-*growing species used in wood biomass production *as a means of maintaining carbon sequestration rates in British forests".* and

*"[The] validation of models developed for intensive even-*aged forestry when applied to other *FMAs [Forest Management Alternatives] and/or provision of more flexible models".*

As such the main focus of this study is on eucalypts, particularly focusing on aspects that will be useful to growing them as SRF.

Table 1.4 Cost effectiveness and average emissions abatement of options for creating forests over a 100 year period (Read et al 2009)

Option	**Cost effectiveness (£ tCO_2^{-1})**	**Cost effectiveness (£ tCO_2^{-1}) excluding traded carbon value**	**Abatement (tCO_2 ha^{-1} y^{-1})**
SRF YC38 eucalypt	**-60.8**	**24.8**	15.1
SRC YC 20 willow	-50.3	58.6	3.7
SRF YC16 eucalypt	**-45.3**	**41.3**	8.4
SRF YC20 eucalypt	**-30.6**	**44.6**	9.5
YC16 SS/DF	-17.3	-2.8	12.9
YC12 SS ACF shelterwood	-11.2	-0.1	9.7
YC 12 SS/DF	-9.6	5.3	9.1
YC12 SS/DF ACF selection	-4.7	8.1	9.1
YC4/10/14 mixed broadleaf/ conifer woodland ACF selection	11.2	25.9	7.9
YC4 native pinewood	21.1	21.1	7.0
SRF YC12 native species	34.3	114.6	4.5
YC4 native broadleaved woodland	40.7	40.7	8.4
YC6 broadleaved farm woodland	72.7	75.8	5.2

The assumptions on value of carbon traded are £21 tCO_2^{-1} in 2009 increasing to £200 tCO_2^{-1} in 2050. Negative values of cost effectiveness represent a positive financial return due to the values of traded carbon and are therefore more financially attractive.

1.6 Important questions, Existing information, approaches and gaps in information

An overview of important questions relating to the objectives of this study, existing information and the gaps in knowledge prior to this study are described in Table 1.5.

Table 1.5 Objectives, important questions, current sources of information, approaches and data gaps and constraints relating to this study.

Objective	Important questions	Current sources of information	Approach	Data gaps and constraints
1. To identify the species and provenances of eucalypts most suitable for biomass production in Great Britain.	Which are the eucalypt species that are sufficiently productive to be an industrial source of biomass and can survive climatic extremes of the UK? Are there particular provenances that are superior in terms of growth and survival?	There is published information relating to the Forestry Commission (FC) trials established in 1981 and 1985. In addition a small amount of more recent published and grey material exists. The FC trials provide a useful resource but many are in too poor condition to allow a detailed analysis. A database of FC eucalypt trials has been used to identify those which are replicated and are in reasonable condition and only four trials have been found in total. Three others have been recently measured and two have been analysed by BSc (Hons) students at the University of Cumbria as part of their studies for final-year dissertations (Bennett and Leslie 2003, Cope, Leslie and Weatherall 2008). There are more recent plantings and trials but they represent early growth – for example the ones in Nottinghamshire were planted in 2005/2006 and which were badly damaged in the winter of 2010/2011.	The literature available from Great Britain and also areas with a similar climate such as Ireland was reviewed. FC replicated trials in reasonable condition were assessed and the results analysed. Most of the FC trials were measured until age five years and their survival after the cold winter of 1981/82 and 1985/86, reported in Evans (1986) will be used with other sources such as Purse and Richardson (2001) to determine the suitability of eucalypt species across the UK.	Evans' (1986) review of the FC trials is based on early growth data. However a more recent review of some trials exists (Purse and Richardson 2001) but based on observations rather than formal measurements and analysis. Only a few of the FC trials were in a sufficiently good state to be usable. Maintenance over much of their lives was poor and there were concerns about early weeding and protection. The few trials that remained in reasonable condition did not give good

				geographical coverage of Great Britain
2. To compare growth of eucalypts with other promising SRF genera.	Is the production of biomass from eucalypts superior to that of other genera? What are the risks associated with using eucalypts compared with other genera?	The 1980's FC eucalypt trials did not include trees of other genera and so comparative data are lacking. Comparison of the growth of eucalypts with adjacent stands of production trees such as sitka spruce in Ireland (Neilan and Thompson 2008) and Corsican pine (Bennett and Leslie 2005) suggest that eucalypts are relatively fast growing. However it is clear that this high productivity is often not achieved (Kerr and Evans 2011). A series of trials was established in Scotland by FC Scotland and by DEFRA in England to test the growth of eucalypt against other genera (Harrison 2010). The results of these trials over the winter of 2009/2010 highlighted the devastating effect of extreme winters on survival of eucalypts.	A small replicated trial was established at Newton Rigg to compare two species with three other species, identified in Hardcastle (2006) as having potential. Growth of the species at this trial was compared with that of the FC and DEFRA funded trials. In addition the trial was used to gather information on LAI, growing season and frost tolerance of species.	The only trials established to compare were recent and so long-term comparative data of growth between genera are not available. The basis for the dissertation was therefore focused on initial growth rates. Data on growth from recent trials were lacking because of high or complete mortality caused by very cold winters of 2009/ 2010 and 2010/ 2011.
3. To develop volume and	Do any of the current volume	While there are several volume functions for *E. nitens* and for cold-tolerant eucalypts	Data were obtained from measurements of stem form from felled trees and from those	There have been no previous assessments of

biomass functions for *E. gunnii*.	functions for cold tolerant eucalypts reliably predict volumes of UK grown *E. gunnii*?	in general, only one volume function has been developed specific to *E. gunnii*, which was developed in France by AFOCEL (2003b). It was not known the degree of precision this estimates volumes of *E. gunnii* grown in the UK. .	measured using a Trupulese optical dendrometer. These data were augmented with that obtained by scans from the Forest Research Leitz Terrestrial Laser Scanner. For felled trees and for those measured using the Trupulse dendrometer, diameters up the stem and total height of the trees were measured and the volume determined by using the diameter and length of the sections. The conformation to existing volume functions was determined and if necessary a new function was to be developed.	stem form of *E. gunnii* in Britain.
4. To estimate yields and patterns of growth for *E. gunnii*.	What is the pattern of growth in *E. gunnii* and at what age can increment be maximised?	Growth curves for *E.gunnii* in the Mid Pyrennes were developed by AFOCEL (2007) but it was not known how reliably these conform to the pattern of growth in UK grown trees. The trees grown by AFOCEL are clonal and subject to intensive silviculture and have grown more rapidly than trees in the UK.	Where available existing growth data were used to characterise patterns of growth. These data were patchy as many trials were measured for up to the first five years but not thereafter, apart from assessments of a very few trials at greater than 20 years of age. Stem analysis was used to determine annual height and diameter growth from felled trees. Trees were felled and measured at two contrasting sites; Chiddingfold in south east England and Glenbranter in south west Scotland.	There were no continuous, annual time-series data sets for growth of *E. gunnii* in the UK for stands over five years old. Trial plantings on an operational scale at Nottinghamshire County Council were devastated by the early and intense cold period during November 2010. Ones

				close by at Thoresby estate, which were planted in 2001 and nine years old were killed during the same winter. This precluded use of these sites to obtain continuous time series data, but standing dead trees at Thoresby were used to develop volume functions and early data from Daneshill to produce growth functions. Stem analysis is time-consuming and so a relatively small number of trees only can be sampled. Also the Forestry Commission was unwilling to fell large numbers of these trees as they are a potential source of seed. There were very few stands of *E. gunnii* across the UK.

1.7 Overview of Chapters

The following sections provide a summary of the four chapters, other than the Introduction and the Discussion and Conclusion.

Chapter 2 Literature review

A review of current literature was made to provide background to the other studies. There is a long history of growing eucalypts in the UK. The review was split into two parts; one on history of eucalypts in the UK, and the other which focused on the potential of eucalypts for provision of woody biomass in the UK.

The first half of Chapter 2 describes the history of eucalypts in the British Isles and their potential. Eucalypts have been planted successfully in Great Britain and Ireland since the mid nineteenth century. While most of the seven hundred species of eucalypts are not suited to the relative cold of the climate of the British Isles, trials in Britain and Ireland have shown that certain species and subspecies can grow successfully. Further, some eucalypts are the fastest growing trees in the British Isles with mean annual increments of between 25 $m^3 ha^{-1} y^{-1}$ and 38 $m^3 ha^{-1} y^{-1}$ being reported (Purse and Richardson 2001). Rapid development of a wood biomass energy sector has encouraged a reassessment of the potential of eucalypts grown on short rotations as a source of energy.

This second half of Chapter 2 provides a discussion of the potential of, and constraints to, using eucalypts for biomass in the UK and provides a tentative list of recommended species, their potential growth rates and their advantages and disadvantages. Considerable potential exists in the UK for utilising woody biomass, grown under short rotation forestry management systems, to produce electricity or heat. There are benefits to using biomass in generating heat and power the main environmental benefit being from substituting for fossil fuel combustion and consequent carbon emissions. Woody biomass production in short rotation forestry involves growing single stemmed trees rather than coppice over rotations of between 10 and 15 years. Eucalypts are particularly suited to such biomass production as they exhibit relatively high wood density, have suitable chemical characteristics and can be easily harvested all year around using conventional machinery if a single-stemmed growth form is maintained.

The UK has a climate that is not well suited to the majority of eucalypts. However, there is a small number of eucalypt species that can withstand the stresses caused by frozen ground and desiccating winds or sub-zero temperatures that can occur. These species are from more southern latitudes and high altitude areas of Australia. However, even the most cold resistant species can be damaged by UK winter climate extremes and therefore careful matching of species to site environmental constraints is critical. Informed decision making is made problematic by the small area and limited distribution of current planting, although it is clear that particularly cold areas and for most species, sites with poor drainage should be generally avoided.

Chapter 3 Identification of species and provenances suited to Britain

Four trials established in the 1980s under a programme directed by Professor Julian Evans were assessed to provide information on additional information on origins that might be productive as producers of biomass in southern England. Few of the trials established during this period were in sufficiently good condition to warrant assessment.

The first part of Chapter 3 describes results from three trials from a set of four, planted in 1985 to determine origins of snow gums (Eucalyptus pauciflora) and a small number of origins of other species that would be productive in Great Britain. The fourth trial at Wark in north east England was not assessed as survival had been very poor.

The trials were assessed for height, diameter at breast height and survival. The sites were in southern England but differed in their climate, particularly maritime influence, summer moisture deficit, and in their altitude and soils. Self thinning and windthrow within the trials posed constraints on those origins that performed better. There were, however, some origins that showed good growth and survival across two or three trials. E. pauciflora ssp debeuzevillei from Mount Ginini showed superior growth and survival at Thetford (East Anglia) and Torridge (Devon), while E. pauciflora ssp niphophila from Mount Bogong exhibited high survival across all three trials. If biomass production is the objective, many of the origins are too slow growing and faster growing species are available, including other eucalypts. The Mount Ginini origin of E. pauciflora ssp debeuzevillei was estimated to produce 7 m^3 ha^{-1} y^{-1} at Thetford and 10 m^3 ha^{-1} y^{-1} at Torridge at 26 years old, while ash is predicted to yield 6.3 m^3 ha^{-1} y^{-1} and Sitka spruce, 13 m^3 ha^{-1} y^{-1} on a similar rotation. A eucalypt species other than snow gum that showed some promise was E. perriniana, origin ‘Smiggin Hole’ which yielded a mean annual increment of 25 m^3 $ha^{-1}y^{-1}$ over 24 years at

Chiddingfold (Sussex). However, survival was poor at Thetford and so it may be suited to only the warmest of sites (above accumulated temperature (AT5) of 1900 degree days).

The second part of Chapter 3 describes results from a trial of six cold-tolerant eucalypt species, planted in 1981 near Exeter, in south west England. This was assessed in 2010 for height, diameter at breast height and survival. The predicted soil moisture deficit on the site is low and it is relatively warm (AT 1662.5) and sheltered (DAMS 12.6), although it experienced a succession of cold winters in the 6 years following planting. The growth of some E. delegatensis was very rapid; the productivity of the seedlot having best survival (48%) was 38 m^3 ha^{-1} yr^{-1} although this seedlot was collected from one mother tree and was unrepresentative of the broader population at that location. Of the closely-related species E. johnstonii and E. subcrenulata, seedlots recorded as E. johnstonii had poor average survival (26%) and growth (7 m^3 ha^{-1} y^{-1}), while E. subcrenulata seedlots from Mount Cattley, Tasmania exhibited both good average survival (68%) and growth (25 m^3 ha^{-1} y^{-1}), with progenies from particular individual mother trees performing substantially better. Based on the results of this assessment, selected sources of E. subcrenulata appear~~s~~ suitable for woody biomass production in sheltered sites in south west England. Of the closely related E. coccifera and E. nitida, the former showed better survival, at 18% against 5%. The poor performance of these species is surprising, as the latter species, which is less cold-tolerant, has grown and survived well elsewhere in south west England, and overall survival of both species at Exeter in 1995 was 60%. The good cold-tolerance and growth of certain seedlots from single mother trees within provenances suggests that much of the variation in performance of all species is genetically determined at family rather than provenance level. The larger surviving trees in the trial could provide germplasm for further trials, with the possibility of later conversion of parts of the Exeter trial to seed stands.

Chapter 4 Comparison of SRF species at Newton Rigg

Chapter 4 describes results from a randomised complete block trial, testing five species across six replicates that was established in 2009 on pasture land at the Newton Rigg Campus of the University of Cumbria. The aim of the trial was to compare the growth and survival of Eucalyptus nitens, Eucalyptus gunnii, ash (Fraxinus excelsior), sycamore (Acer pseudoplatanus) and alder (Alnus glutinosa). In addition, frost and browse damage was assessed for the two eucalypts over the winter of 2009-2010.

The first part of the chapter describes growth of trees species and investigates some of the factors influencing this. Considerable differences were apparent in growth rate and survival between species, with alder showing particularly rapid growth, balanced with excellent survival. The two eucalypts planted exhibited fast growth but mortality proved high over the severe winter of 2009-2010, with only a few E. gunnii surviving for two growing seasons. The study examined some of the characteristics of contributing to growth. There were differences between species in terms of leaf area, with E. gunnii exhibiting a particularly high leaf area. Leaf area to stem weight was low for ash relative to other species. Specific leaf area was also low, a trait shared with E. gunnii, which suggests that these species invest highly in each unit of leaf area. The length of the growing season was longest for E. gunnii (estimated) and alder, enabling them to maintain growth for a longer period over the year. The effect of leaf area and growing season on productivity was demonstrated by developing a growth potential index, by multiplying growing season by leaf area, and this explained 56% of the variation in stem dry weight between trees. The results show that on sites similar to the one planted in this experiment, alder would be a good candidate for producing woody biomass, exhibiting rapid growth and high survival. However, if the objective of planting is sequestration to offset greenhouse gas emissions, alder may not be appropriate due to emissions of N_2O and CH_4 (Mander et al 2008).

The second part of the chapter presents the results of a survey of frost damage of the two species of eucalypts. Cold is the main climatic constraint to planting eucalypts in Britain and the winter of 2009-2010, the coldest in thirty years proved to particularly challenging for their survival. Damage to transplants planted in May 2009 of two species of eucalypts, Eucalyptus gunnii and Eucalyptus nitens was assessed over winter at a trial in Cumbria, northern England. Larger trees were found to have exhibited less cold damage by the end of January, but by May there were no significant differences in survival due to tree size. By late January, there were statistically significant differences in damage between E. gunnii and E. nitens with the former being more cold tolerant. However, damage at the end of January, after minimum temperatures of -14^{o}C did not appear serious, yet by May the survival of E. gunnii was 37% and for E. nitens was less than 1%. It is proposed that the severe cold alone did not kill the trees but rather this in conjunction with a long period of frozen ground but warm day temperatures resulted in severe desiccation and death of most of the trees. As larger trees exhibited relatively less frost damage it is recommended that intensive silviculture be practiced to ensure trees are between 1 and 1.5 m tall prior to their first winter to reduce the extent of damage through frost.

The final part of Chapter 4 describes the results of an assessment of browse damage over the winter of 2009-2010, which showed clearly that E. gunnii is more palatable than E. nitens to mammalian browsers. E. gunnii has been described previously as being palatable (Neilan and Thompson 2008).

Chapter 5 Characterising volume and growth

This chapter describes the first attempt to identify appropriate two variable (dbh and height) volume equations and develop growth functions for Eucalyptus gunnii grown in the UK. The precision of two volume equations were compared, one devised by AFOCEL (2003a) from plantations of E. gunnii and Eucalyptus X gundal in France and another developed by Shell (Purse and Richardson 2001) for cold-tolerant eucalypts in Chile. The AFOCEL equation gave a better fit in terms of bias, for all but the smallest of trees, as the Shell function consistently underestimated stem volume.

Functions relating height and age, height and dbh, cumulative volume and age and mean annual increment and age were developed using historic data, stem analysis from trees at Chiddingfold in southern England and at Glenbranter in southern Scotland. The historic data indicated that stands had grown at 16 m^3 ha^{-1} y^{-1} or approximately 8t ha^{-1} y^{-1}at an age of twenty years. The stem analysis of nine trees at Chiddingfold and of two trees at Glenbranter indicated much lower yields of 7 m^3 ha^{-1} y^{-1} at age 28 years and 4.5 m^3 ha^{-1} y^{-1} at 30 years respectively.

There is evidence that yields can be considerably higher where intensive silviculture has been practised, such as at Daneshill in Nottinghamshire, where trees attained a height of 10.6m in five and a half years. Potential yields are often compromised by high mortality and a priority should be to identify areas in the UK where E. gunnii can be grown with low risk and also to choose well adapted genetic material.

Chapter 2 Literature Review

The following chapter is divided into two principal parts, the first being a history of eucalypts in the British Isles and the second being a review of literature relevant to growing eucalypts on short rotations in Britain. The first sub-section was published as an article in the Quarterly Journal of Forestry in 2012, the full citation being:

Leslie, A.D.; Mencuccini, M. and Perks, M. (2011) Eucalyptus in the British Isles. Quarterly Journal of Forestry. 105 (1): 43-53.

Figure 2.3 has been updated incorporating the results from later work undertaken for this thesis.

The second sub-section was published as an article in Applied Energy in 2012 the full citation being:

Leslie, A.D.; Mencuccini, M. and Perks, M. (2012) The potential for Eucalyptus as a wood fuel in the UK. Applied Energy 89 (1): 176-182.

They are presented in the next two sub-sections. The articles were the results of my work, supported by input from my supervisors, Dr Maurizio Mencuccini and Dr Mike Perks.

2.1 History of eucalypts in the British Isles

Introduction

Eucalypts have been widely planted, with an estimated 13 million ha worldwide (AFOCEL 2004). Of the seven hundred species (Poke et al, 2005), it is only a relatively small proportion that are adapted to temperate climates, such as that of the British Isles. If the position of British Isles in the Northern Hemisphere is compared with that of Australia in the Southern Hemisphere (Figure 2.1), it is apparent that only eucalypts from the extreme south of Australia and then those from colder areas, such as Eucalyptus gunnii (Hook. f.) and Eucalyptus nitens ((Deane and Maiden) Maiden) are likely to be suited to the British climate. Most of the Eucalyptus species in the British Isles have been introduced in a sporadic and speculative manner, without consideration of matching climates in their home ranges with those of parts of the British Isles. This has meant that the majority of species introduced have exhibited poor survival and growth. However, it is clear that there is a restricted range of eucalypts that will survive the extremes of cold and the frequency of unseasonal frosts that are part of the climate of the British Isles and further can also produce attractive yields. When examining the potential and site limitations of specific eucalypts, one difficulty is that they have only been planted in a limited number of locations and over small areas. Also, many of these plantings have established in collections in arboreta situated in parts of the British Isles with a milder climate.

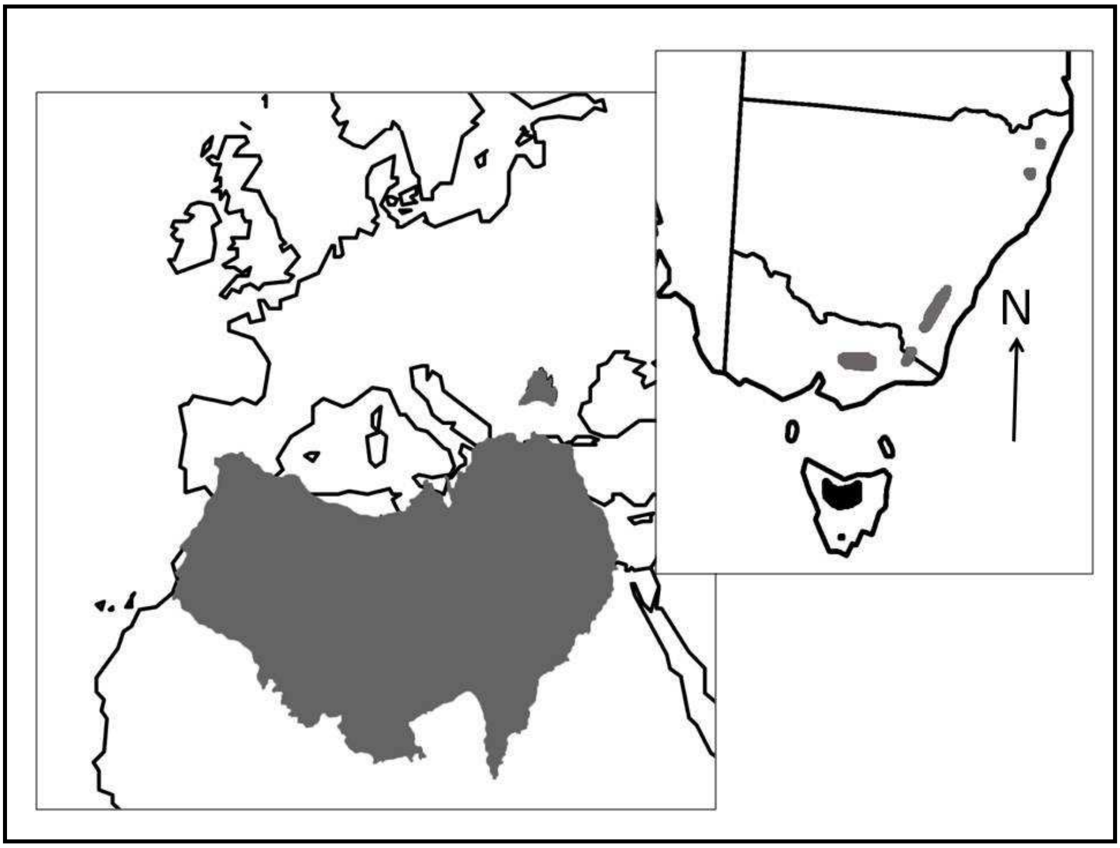

Figure 2.1: Comparison of latitude and area of Europe and Australia (adapted from Turnbull and Eldridge1983). Insert on the top right. The natural distribution of *Eucalyptus gunnii* and *Eucalyptus nitens* in southern Australia are given in black and grey, respectively (Brooker and Kleinig 1990).

Eucalypts have certain traits that make them particularly suited to planting for biomass or bulk fibre production, such as rapid growth, broad site tolerances and moderate wood density. Interest in using eucalypts as a source of biomass for energy has increased in recent years in the British Isles, particularly in Great Britain. In Britain, incentives for adoption of renewable sources of energy, such as Renewable Obligation Certificates, promote the use of renewable energy sources and particularly biomass crops. Two recently proposed schemes supporting renewable energy in Britain are likely to have a positive impact on the financial viability of biomass as a fuel: the Renewable Heat Initiative (Pigot 2009) and the earlier Low Carbon Buildings Programme, both of which will support small-scale generation of electricity. Recently, here have been a considerable number of proposals for biomass power plants, including Drax power which is further developing its co-firing capacity and establishing dedicated biomass plants. It is estimated that by 2017 Drax will need 6.2 million tons of wood pellets or equivalent biomass per year (Forest Energy Monitor 2009). In Ireland the Biomass Energy Scheme supports planting of willow and Miscanthus, covering 50% of establishment costs (Bioenergy Site 2008), while support is also available for installation of facilities to produce electricity and heat from renewable sources through the REFIT (Renewable Energy Feed In Tariff) programme (Department for Communications, Energy and Natural Resources, 2009). This section aims to provide a history of eucalypts in the British Isles, highlighting those species that are suited to the climate and productive enough to have potential as a source of wood fibre. It ends with a prediction of the future role of eucalypts in forestry in the British Isles.

The early history of eucalypts in the British Isles

Eucalypts were first introduced to Europe from material collected by Furneaux during Captain James Cook’s second voyage to Australia in 1774. It is likely that the first species raised in Britain, at Kew Gardens was Eucalyptus obliqua (L’Hérit) from New South Wales (Aiton 1789). By 1829 Eucalyptus globulus (Labill.) was being cultivated in continental Europe, while by 1838 it had been introduced to the Scilly Isles (Martin 1950). There is some disagreement as to which was the first eucalypt planted outside a greenhouse in Britain. Elwes and Henry (1912) describe E. gunnii as being the first species grown in Britain in the open, being a tree planted at Kew Gardens. This was 20 feet (6 metres) tall by 1865 (Smith 1880 in Elwes and Henry 1912). However, the first successful planting of a eucalypt is often attributed to James Whittingehame in East Lothian, Scotland probably in 1852 (Elwes and Henry 1912) from seed collected by James Balfour from Mount Wellington Tasmania, (University of Sydney, no date). The tree survived even the severe frost of 1894 and was still alive as a large tree in 1961 (MacLaggan Gorrie 1961). The identity of the tree has been debated, being identified as Eucalyptus gunnii (McDonald et al 1957), as a hybrid, probably with Eucalyptus urnigera (Hook.f) (Elwes and Henry 1912, McLaggan Gorrie 1961), or as pure E. urnigera (University of Sydney no date). Progeny of the Whittingehame eucalypts have been planted widely, including in Kew, London and

Kinlochourn, Inverness, where they were still growing in good health in the 1960's (McLaggan Gorrie 1961). Trees from some other early plantings still survive in Britain. Purse (2005) describes the healthy condition of the remaining trees of a 1887 planting of E. gunni, at Brightlingsea, Essex. These were planted from seed sent from Argentina (Elwes and Henry 1912) and have survived many severe winters including that of 1962/1963 when the sea near the town froze (Purse 2005). In Ireland the first planting of eucalypts also dates from Victorian times and a large E. globulus, planted in 1856 was still alive in 1983 (Evans 1983).

During the 1870s and 1880s, the planting of E. globulus became fashionable in Europe, especially in the Mediterranean due to its fast growth and the mistaken belief that the tree and extracts derived from it had anti-malarial properties. This interest in eucalypts spread to the British isles and even E. globulus, a relatively cold intolerant species, was planted and while generally not suited to the British climate one planted at Garron Tower, Northern Ireland still survived in 1961 (MacLaggan Gorrie 1961) Many other species were planted during the 19th century and early 20th century, and there were probably over thirty species in the British Isles at the beginning of the 20th century (McDonald et al 1964). Plantings were particularly successful in warmer areas of Britain, such at Kilmun Arboretum in Argyll, where 21 species still grow succesfully (Evans 1980a). Despite this interest, it is likely that in the 19th century, eucalypts were rare trees in Britain.

Over the decades of the 20th century, there were many reports of the potential of eucalypts as a tree for wood production (Elwes and Henry 1912, Forbes 1933, McDonald et al 1964, Barnard 1968, Marriage 1971) particularly of the attractive growth rates that could be obtained. However these authors also noted the limited range of species that could survive the extremes of cold experienced in the British Isles. Some species were noted for their cold-tolerance; for example, a survey, undertaken after a particularly severe late frost in May 1935, that caused widespread damage to trees across Britain including native species, described certain species of eucalypt, notably E. gunnii and Eucalyptus coccifera (Hook f.), as being undamaged (Forestry Commission 1946).

In Ireland important collections of eucalypts were established between 1908 and 1910 at Mount Usher and nearby at Avondale Forest in County Wicklow and also in Northern Ireland at Castlewellan in County Down (Evans 1983). Between 1925 and 1961 experimental plots of eucalypts were established in Ireland and growth of several species was promising in the mild Irish climate, notably Eucalyptus viminalis Labill, E. urnigera, Eucalyptus johnstonii Maiden, Eucalyptus delegatensis RT Baker and Eucalyptus dalrympleana Maiden. A detailed presentation of results can be found in Neilan and Thompson (2008) and selected growth and survival data from a trial established in 1935 is presented in Table 2.1 to indicate the high growth rates that have been achieved.

Table 2.1: Growth of selected species and trial sites from plantings from 1935 at Glenealy, County Wicklow, planted at 1.8m x 1.8m spacing (Neilan and Thompson 2008). Notes: [1] "mountain" provenance as coastal provenance did not survive, [2] from a 1934 trial at the same site, with 11 year, 21 and 24 year results.

	% survival	**Height (m)**			**Dbh (cm)**		
Species	10 yr	10 yr	20 yr	23 yr	10 yr	20 yr	23 yr
E. viminalis[1]	74	3.7	12	13	2.5	14.6	10.8
E. urnigera	96	4.8	16	18	3.8	14.6	12
E. johnstonii	98	7.8	18	21	7	12.1	15.2
E. delegatensis	100	4.9	14	16	5.1	14.6	15.2
E. dalrympleana [2]	100	4.9	14.8	17.5	7	15.2	17.8

Other work in Ireland provided evidence supporting the use of eucalypts as fast growing sources of biomass. The quadrupling in price of oil in 1973 reinvigorated interest in wood as a potential fuel in Ireland. McCarthy (1979), reporting on two years of growth in a series of biomass trials across four sites in Ireland of conifers and broadleaved species, noted that the one eucalypt, Eucalyptus johnstonii Maiden. was a promising candidate for biomass production, except on a blanket bog site.

An assessment made in the 1976/1977 of amenity plantings on the Devon/ Dorset border, established between 7 and 30 years earlier provided interesting results on the merits of thirteen species of trees as a source of fuel wood (Marriage 1971). The trees tested included six eucalypts, Eucalyptus cordata (Labill.), Eucalyptus delegatensis (RT Baker), Eucalyptus glaucescens (Maiden & Blakely), Eucalyptus gunnii, Eucalyptus macarthuri (Deane & Maiden) and Eucalyptus regnans (F. Muell.). All of the eucalypts grew faster than the trees of other genera, including Fraxinus excelsior.L, Nothofagus obliqua (Mirb.) Bl., Pinus pinaster (Ait.), Pinus radiata (D. Don) and Populus X robusta (Schneid) (Marriage 1971). Indeed, Marriage (1971 p203) ends the article "in 10 years [eucalypts] will produce as much wood as ash in 30 years".

In 1981 the Forestry Commission established a series of formal trials across nine sites (Figure 2.2, Table 2.2) to identify species and origins adapted to the British climate. Species included in these trials were selected on the basis of observations from plantings in arboreta, gardens and the few existing experimental plots (Evans 1980a) that showed some eucalypts exhibited attractive attributes for production forestry, particularly:

- That they will attain large dimensions; growing to at least 20m in height
- And that they grow rapidly in their early years (1-2m height growth per year in the first ten years)

The species tested comprised sub-alpine species from temperate south-eastern mainland Australia and Tasmania. The winter of 1981/82 proved to be one of the harshest in decades which was fortuitous in that it eliminated from consideration species that were not suited to the extremes of the British climate (Evans 1983; Evans 1986). The results supported previous observations that some eucalypts were sufficiently frost-hardy to survive extremely cold climatic events in the UK. In 1984/85 there was another severe winter and so by 1986 it was clear which species could be planted successfully in Britain (Evans 1986). This eliminated a large number of potential species and seed origins but three species; E. gunnii, E. pauciflora ssp niphophila and E. pauciflora (Sieb. Ex Spreng.) ssp debeuzevillei (Maiden L Johnson & D Blaxell) were noted to be sufficiently frost hardy for British conditions (Evans 1986). On the three sites that were exposed to the coldest temperatures during the winter of 1981/82 (Alice Holt, Thetford and Wark) every species was killed except E. pauciflora ssp debeuzevillei, E. pauciflora ssp niphophila and E. gunnii. Further, the origins that had survived were the same, providing useful information on populations suited to the extremes of the British climate.

In 1985 a further set of trials was established across three of the original sites ranging from the lowlands of southern England to an upland site at Wark, near Kielder (Figure 2.2, Table 2.2) to test the growth and survival of snow gums which are subspecies of E. pauciflora and a few other species, such as E. camphora (RT Baker), E. perriniana (F. Meull ex Rodway), E. stellulata (Sieb ex DC) and E.viminalis. These followed on from trials using large plots of E. pauciflora ssp niphophila and E. pauciflora ssp debeuzevillei that were established at four sites in 1983 and which had shown reasonable growth and good survival (Evans 1986).

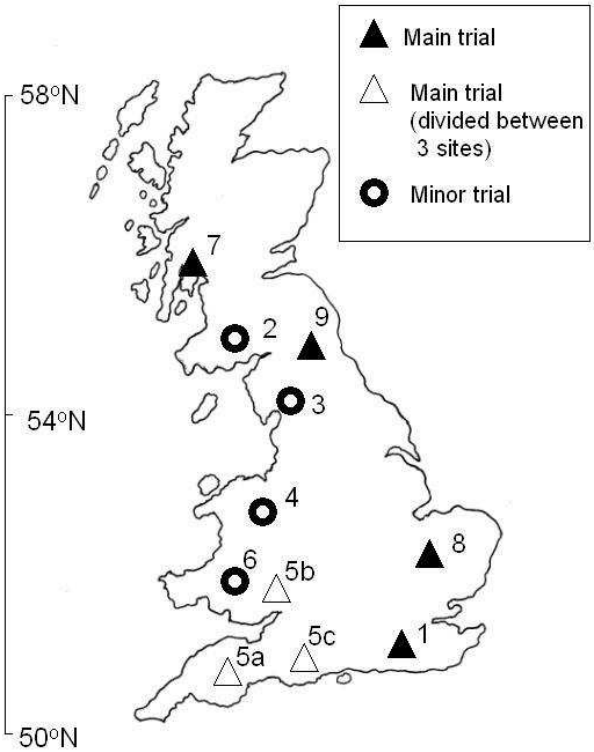

Figure 2.2: Sites of main eucalypt trials established in the 1980's in Great Britain. 1 = Alice Holt, 2 = Dalmacallan, 3 = Dalton, 4 = Dyfnant, 5a = Exeter, 5b = Tintern, 5c = Wareham, 6 = Glasfynydd, 7=Glenbranter, 8=Thetford, 9 = Wark. (Evans 1986)

Table 2.2: Details of the trial sites established in the 1980s and minimum temperatures in December 1981 and January 1982 (Evans 1986)

Site No.	**Location**	**National Grid Reference**	**Region of Britain**	**Altitude (m a.s.l)**	**Minimum temperature (°C)**	
					Dec 1981	Jan 1982
1	Alice Holt	SU988303	SE England	60	-14	-19
2	Dalmacallan	NX703964	S Scotland	320	-16	-19
3	Dalton	SD453880	Lake District	65	-12	-12
4	Dyfnant	SH940169	N Wales	500	-11	-13
5a	Exeter	SX882827	SW England	170	-6	-7
5b	Tintern	SO529052	SE Wales	222	-12	-16
5c	Wareham	SY883927	S England	30	-10	-12
6	Glasfynydd	SN860228	S Wales	440	-10	-14
7	Glenbranter	NS094965	W Scotland	140-220	-11	-16
8	Thetford	TL800900	E Anglia	15	-20	-18.5
9	Wark	NY794789	NE England	210	-17	-23

During the 1980s research was also conducted to investigate the potential of willows Salix spp), poplars (Populus spp), alders (Alnus spp) and eucalypts for biomass as short-rotation coppice. In trials established in 1981/82 yields of E. gunnii ssp archeri were comparable to the poplar and willow clones tested (Potter 1990). At a trial established at Long Ashton in 1986, yields from the Eucalyptus gunnii was far superior to the red alder (Alnus rubra Bong), the poplar clones and the willow clones (*Salix viminalis* (L.) Bowles Hybrid) in the experiment. Yields from E. gunnii ranged from 16 - 22 odt ha^{-1} y^{-1} whereas willow, which was the next most productive material produced 7-8 odt ha^{-1} y^{-1} (Mitchell et al 1993). The reason for the dismissal of eucalypts for short rotation coppice was the susceptibility to silverleaf disease (*Chondrostereum purpureum* (Pers) Pouzar) following cutting of the stools. However the seed used to raise the seedlings of E. gunnii ssp *archeri* was from a single parent and it may be that narrow genetic diversity predisposed the stools to attack by this pathogen. It is known that reduced genetic diversity produces less adaptable trees; an investigation of selfing in *Eucalyptus* globulus showed poorer growth in the field when compared with individuals that arose from outcrossing (Hardner and Potts 1995). Furthermore, growing eucalypts as single stems over longer rotations should reduce the damaging impact of silverleaf disease since the trees are cut less frequently.

The history of eucalypts in the British Isles since the 1980s

Following Evans' (1980a, 1983, 1986) work, interest in eucalypts waned, and they were generally dismissed as trees unsuitable for meeting the objectives of production forestry in Britain. Evans (1986 p238) himself commented "until a specific need arises to maximise dry matter per hectare per year, further use of eucalypts … seems unlikely". The introduction of the Broadleaves Policy in 1986 favoured native trees and left no role for eucalypts in forestry; while production forestry remained centred on softwood species.

In 1992 and 1993 a new series of trials was established in Ireland, with E. gunnii and E. delegatensis planted in 1992 and E. nitens and E. delegatensis in 1993. In a review of eucalypts in Ireland, Neilan and Thompson (2008) report that growth in the trials has been excellent. The potential is illustrated by a comparison of adjacent stands at Cappoquin, County Waterford of E. nitens and Sitka spruce (*Picea* sitchensis (Bong.) Carr.), the most commonly planted softwood in Ireland. After 13 growing seasons E. nitens had attained a top height of 22.5m and dbh of 26cm, whereas Sitka spruce achieved a top height of 11.5m and dbh of 11 cm (Neilan and Thompson 2008). Furthermore, if growth after 13 years of E. nitens planted in 1993 at 2m x 2m spacing is compared with that from earlier trials, E. nitens shows a much greater diameter than that obtained at 23 or in some cases 46 years of age by the other species tested in the trials from the 1930s.

During the late 1990s and early 2000s a relatively small group of individuals and organisations began to investigate the silviculture of eucalypts through small-scale plantings and trials. Companies such as Primabio and Forestry Business Services began to provide advice to private individuals and organisations interested in growing eucalypts for biomass energy. An article by Purse and Richardson (2001) described evidence of fast growth from a range of sites. They reported on a small replicated, privately owned trial, established on a reasonably exposed site at an altitude of 130m above sea level, north of Tiverton, Devon in 1993. Of the species planted E. nitens proved to be the most productive, while E. dalrympleana (Maiden), E. fastigata (Deane & Maiden) and E. delegatensis (RT Baker) also showed good growth (Purse and Richardson 2001).

Visits were also made by Purse and Richardson (2001) to eight of the Forestry Commission trials in southern England and as far north as Nottingham between 2000 and 2001. It was found that E. gunnii and E. pauciflora had survived well, while Eucalyptus nitens and E. delegatensis showed poor survival but rapid growth. Comments were also made on the poor weed control in these trials observed during visits made in 1987. Purse and Richardson (2001) argued that competition between the eucalypts and weeds has reduced their growth and that the trials therefore underestimated the potential of eucalypts in the UK and that the competition would also have heightened damage by frost.

Concern about climate change and also energy security has raised awareness of a possible role for woody biomass as part of the means of meeting the energy needs of the UK (McKay 2006). This encouraged the development of a Strategy for England's Trees, Woods and Forests (DEFRA 2007a) which largely ignored the potential of dedicated energy crops such as eucalypts, focusing instead on obtaining wood fuel from under-managed woodlands. It was initially individuals in the private forestry sector that recognised a potential new role for eucalypts in Britain, grown rapidly on short rotations for energy and using high standards of silviculture (Purse and Richardson 2001). The approach adopted marked a change from the use of short rotation coppice (SRC) because the material produced is single-stemmed and the rotation was longer, being greater than 10 years and providing woody material of between 10 and 20 cm diameter at breast height (dbh) (Hardcastle 2006). The approach, known as short rotation forestry (SRF) differs also from SRC in that the material is capable of being harvested using conventional forestry harvesting machinery, whereas SRC is harvested using modified agricultural equipment.

In 2005 Nottinghamshire County Council embarked on an ambitious project to establish an energy forest at Daneshill, on the site of an old munitions works. This comprised a set of experiments and also operational plantings, covering an area of 30 ha. Trials included a species trial, a trial comparing line and intimate mixes of E. nitens and E. dalrympleana and a comparison of establishment methods. On the whole, early results have been encouraging, with E. nitens achieving a height of 8-10 m in four years and E. gunnii a height of 8-10 m height over five years. Frost in the first year of planting meant that areas of E. nitens needed to be largely replanted but the E. gunni proved hardy and now there are some fine plantations of the species.

The increasing level of interest in Eucalyptus led to further reassessments of Forestry Commission trials from the 1980s, such as one at Thetford and Glenbranter. The Thetford results showed the high level of cold tolerance of E. gunnii, which had grown and survived relatively well, while all E. nitens had been killed by the extremely cold winter of 1981/82 (Bennett and Leslie 2005). Findings from Glenbranter, an E. gunnii provenance experiment supported earlier results by Evans (1986) that showed that origins from Lake MacKenzie exhibited superior survival and growth to others (Cope, Leslie and Weatherall 2008). Most recently, a formal assessment of a snow gum trial in Chiddingfold, Surrey showed the main species tested, E. pauciflora, to have similar rates of growth to E. gunnii and as such, to be much slower growing than E. nitens.

Adopting some of the recommendations from a study by Hardcastle (2006), DEFRA supported a series of trials in England of SRF to collect data on establishment costs, yields and environmental impacts, while a similar series of experiments was funded in Scotland by Forestry Commission Scotland. In 2009 three trials sites were planted in England in Cumbria, Devon and Lincolnshire, predominantly with E. nitens. Experiments in Scotland have focused on ash (Fraxinus excelsior L.) as a potential wood fuel species (McKay pers comm. 2009). Smaller trials have also been established, for example a trial of SRF species, testing different eucalypts species, has been established between 2008 and 2009 at Drumlanrigg, near Dumfries in 2008 by Buccleuch Estates, at the Penrith Campus of the University of Cumbria, and at Little Sypland, near Kirkubright by UPM Tillhill.

The future for *Eucalyptus* in the British Isles

In January 2008 the European Union set a target reduction of 20% in greenhouse gas emissions by 2020, compared with levels in 1990 (Poyry 2008). As part of this target, the UK government aims to produce 15% of domestic energy from renewable sources, a ten-fold increase in current levels (Poyry 2008), while in Ireland, the target is a more modest increase to 7.4% of energy from renewable sources from the 2008 contribution of 4.1% (Sustainable Energy Ireland 2009). A study in the UK (Read et al 2009) calculated that using biomass to produce heat is the cheapest way of increasing the proportion of renewable energy. Further, wood fuel is more attractive than some other sources of renewable energy as the technology that is already tried and tested and it has the capacity to meet peaks in demand for heat and electricity. A report on the role of forests in the UK on combating climate change estimates that emissions of as much as 7 MT CO_2 could be avoided by the substitution of fossil fuels with wood fuel (Read et al 2009). The increase in the number of ROCs (Renewable Obligation Certificates) for energy generated from dedicated biomass crops and the announcement of a RHI (Renewable Heat Initiative) should make the use of woody biomass energy crops more attractive when producing heat. In Ireland the White Paper on sustainable energy (Department of Communications, Marine and Natural Resources 2007) states that combined heat and power, particularly using biomass will contribute 400MW of energy by 2010 and 800MW by 2020.

If woody biomass crops are to be used more widely as a source of energy in the UK and Ireland then eucalypts are likely to play an important role due to their high productivity. Evans (1980a) considered E. nitens to be possibly the fastest growing tree in Britain and subsequent findings support this assessment, with reports of mean annual increments of 37 m^3/ha/yr at rotations of 8 years (Purse and Richardson 2001). Even slower growing species, such as E. gunnii are reported to attain mean annual increments of 25 m^3/ha/yr on rotations of 11-12 years (Jones pers. comm. in Purse and Richardson 2001).

In general there can be an inverse relationship between cold-tolerance of commonly planted eucalypt species and their growth rates, for example E. nitens is considerably faster growing than E. gunnii yet is also more susceptible to damage during cold periods, particularly those that are unseasonal. This is illustrated in Figure 2.3, which shows estimates of annual height growth and the minimum temperatures that can be tolerated when hardened by eucalypt species that have been planted successfully in Britain and Ireland. As such, it is crucial that our understanding of the site limitations of the different species is refined, particularly the risks from extreme climatic events, notably extremely cold winters such as 1963/4, 1981/2 and 2009/10. While there is evidence that a number of species have grown successfully across a range of plantings, to date E. gunnii and E.nitens are the two most widely established species under plantation conditions. E. nitens has proven to be the most productive of the species tested and is an obvious choice for warmer sites with good rainfall. It also has the attraction of being extensively planted elsewhere so its silviculture is well understood. However E. gunnii, although slower growing and palatable represents a lower risk to damage by climatic events as it can tolerate longer periods of more intense cold and also is little affected by waterlogging of soils (Kirkpatrick & Gibson 1999). A first attempt to define site requirements within EMIS (Electronic Management Information System) for SRF species, including eucalypts, has been made by Perks and Ray (in draft).

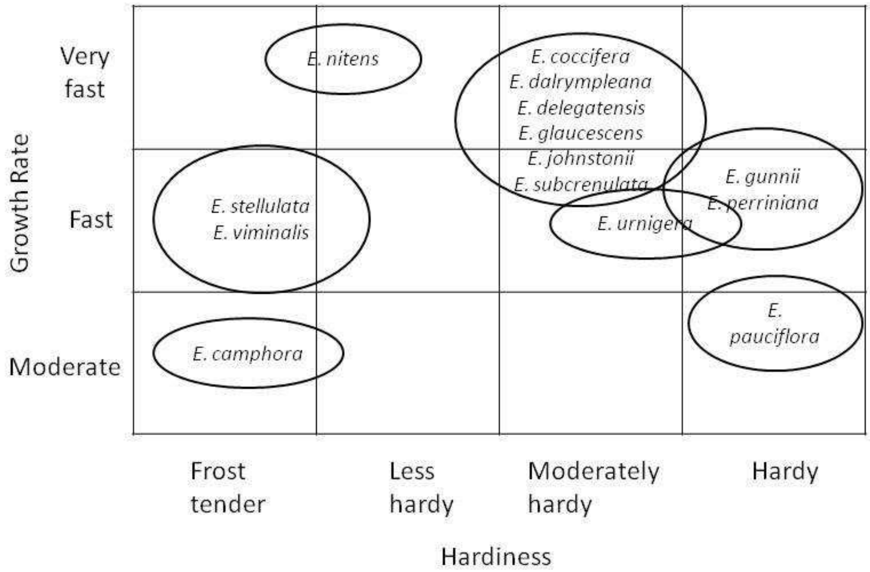

Figure 2.3: Height growth and minimum temperatures tolerated (when hardened) by different eucalypt species. Growth rates (height): very fast = >2 m/year, fast = 1.5m – 2 m/year and moderate = 1 m – 2 m/year. Hardiness: less hardy = likely to survive long periods of –6 and short ones of –9°C, moderately hardy = likely to survive long periods of –6 to –9°C and short ones of –14°C, hardy = likely to survive long periods of –10 to –14°C and short ones of –16°C and very hardy = likely to survive long periods of –10 to –14°C and short ones of –18°C. Compiled from information from Brooker and Evans 1983, Evans 1986 and field observations.

A considerable threat to the adoption of eucalypts more widely is the use of inappropriate genetic material. For several species there is clear evidence of differences between and within origins of cold-tolerant species (Evans 1986) and for some time using cold hardy origins has been recognised as being essential (Barnard 1968, Evans 1986). Evans (1986) describes superior origins of E. nitens, E. gunnii, E. pauciflora, E. delegatensis. However obtaining seed from sources well adapted to the UK climate has proven problematic, for example many of the remaining natural stands of superior origins of E. gunnii are found in national parks, which restricts opportunities for seed collection (Jinks pers comm 2009).

Recent plantings have relied on nursery stock of unknown or less than optimum origins. There are however promising developments, with Maelor Nurseries importing seed of promising origin directly from Australia and bulking up material through vegetative propagation (Harun pers comm 2009).

The cold winter of 2009/ 2010 clearly highlighted differences in cold tolerance between individuals of E. nitens and is supported by the findings of earlier research, Evans (1986). It is interesting to note that 6-year-old E. nitens has survived relatively unscathed at Alcan plantings in Northumbria which were exposed to minimum temperatures of -15^{o}C (Purse pers comm. 2010). Variation in cold-tolerance within populations should be exploited. Those individuals surviving on particularly challenging sites might provide a source of material suited to the extremes of the British climate. Evans (1986) recommends this approach and noted that some individuals of E. gunnii, E. pauciflora ssp debeuzevillei and E. pauciflora ssp niphophila were capable of surviving -23^{o}C.

Also some species with intermediate characteristics of E. nitens and E. gunnii, i.e., faster growth than E. gunnii but more frost tolerant than E. nitens warrant further investigation. For colder sites, high altitude origins of E. coccifera, an unpalatable and frost-tolerant species are recommended for further consideration by Purse (2009a), who also considers Eucalyptus glaucescens (Maiden & Blakely), amongst other species, to have potential for biomass production in the British Isles. This species is being tested along with two provenances of E. nitens and one of E. gunnii in the DEFRA funded trials in England. Neilan and Thompson (2008) recommended Eucalyptus johnstonii Maiden as being a species worth of consideration for planting in Ireland. A trial in Exeter showed there to be significant differences in height growth between provenances of E. johnstonii (Evans 1986), making provenance selection important.

A further priority is to develop best-practice recommendations for the establishment and management of suitable species. For some species such as E. nitens there is considerable information on its silviculture from other countries, while more limited information on growing E. gunnii in plantations is available from a planting programme in the Mid Pyrenees (AFOCEL 2003a, AFOCEL 2007).

Conclusions

Eucalypts have been planted in the British Isles for over a hundred and forty years. Despite being planted over a relatively narrow range of sites and a restricted area, there are undoubtedly species that are sufficiently frost tolerant to survive severely cold winters across many areas of Britain. Fast growth across a range of sites has meant that many authors have recognised the potential of eucalypts for rapid wood production for pulp (Barnard 1968, Evans 1986) or biomass (Marriage 1977, Hardcastle 2006). There is however a pressing need to identify the potential of species other than E. nitens and E. gunnii and to define the site limitations and quantify the risk posed by climatic events of the various species. A further priority is to identify best practice in terms of establishment and tending for different species across a range of sites.

Acknowledgements

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2.2 The potential for *Eucalyptus* as a wood fuel in Great Britain

Introduction

In order to reduce greenhouse gas emissions and improve energy security the UK Government has made a commitment to source fifteen percent of the country's energy from renewable sources by 2020 (DECC 2009). The lead scenario in the UK renewable energy strategy suggests that 30% of electricity and 12% of heat could be provided through use of renewable sources of energy. Woody biomass is predicted to provide about 2% of the electricity generated in the UK by 2020 (DECC 2009), but it is through the provision of heat that wood fuel is likely to have the greatest impact (Forestry Commission England 2007).

Thinnings and fellings from present sources and from bringing neglected woodlands back into management are unlikely to provide sufficient wood fuel to support the Government's aims and the resource is dispersed with variable ease of access and quality. A complementary approach is to develop sources of woody biomass which aim to produce quality fuel and can established close to the biomass demand, reducing both transportation costs and fossil fuel consumption. Previously the focus on woody energy crops in the UK was directed at short rotation coppice (SRC) but the material produced is of low density, high bark content and high moisture content, making it a less than ideal fuel (Ramsay 2004).

A more recent development is short rotation forestry (SRF), where single stemmed trees are grown over a rotation of more than ten years, producing material of between 10 and 20 cm diameter at breast height (dbh) and able to be harvested using conventional forestry machinery (Hardcastle 2006). A suite of species is under consideration for short rotation forestry. One genus that has attracted attention is *Eucalyptus* due to rapid early growth compared with other tree genera (Evans 1980a) and the potential to use singled coppice in subsequent rotations. However, only a few *Eucalyptus* species are sufficiently cold tolerant to survive and grow well in the UK. This article presents a review of the information on cold-tolerant eucalypts and highlights their potential for commercial cultivation in Great Britain and assesses the potential for using eucalypts as a woody biomass fuel source.

Eucalypts as a productive wood fuel resource

To be economic in producing wood fuel, a species should exhibit the following characteristics (Ramsay 2004):

- Produce (moderately) high density wood
- Have suitable chemical characteristics
- Produce wood that easily dries
- Be easily harvested
- Harvestable using conventional machinery
- Harvestable all year around

Eucalypts can largely meet these criteria: they have potential for high productivity over short rotations, they tolerate a wide range of soils and they commonly exhibit straight stem form in species utilised in production forestry. Furthermore, eucalypts, unlike many trees, do not have a true dormant period and retain foliage which enables growth during warm winter periods. The threshold for growth and photosynthesis in their native climate is around 8^{o}C (Sands and Landsberg 2002), although for *E. pauciflora* the critical temperature is 5^{o}C (Ball et al 1997). Eucalypts are one of the most productive plantation species in temperate forestry, with reported yields in France of 18 m^{3} ha^{-1} year^{-1} over a twelve year rotation with single species clones (AFOCEL 2003b) and up to 35 m^{3} ha^{-1} year^{-1} with hybrid clones

(AFOCEL 2006). Estimates of mean annual increment (stem growth rate) vary with site (soil, climate and biotic influences) and genetic (species and origin) factors. Generally there is a trade off between cold hardiness and growth rates, and also the most cold tolerant species tend to have poor form, which although less important for biomass than for sawn timber will still influence the cost of harvesting, transport and processing. The slower growing, but more cold-tolerant species like E. gunnii have yielded mean annual increments of around 10-15 $m^3 ha^{-1} yr^{-1}$ on a 10-12 year rotation across a series of trials in the UK (Evans 1983) with one report of 25 $m^3 ha^{-1} yr^{-1}$ at 11 years old (Purse and Richardson 2001). Faster growing species such as E. nitens may yield mean annual increments of over 25 $m^3 ha^{-1} yr^{-1}$ (Neilan and Thompson 2008). A comparison of the growth rates and rotations of tree species commonly used in production forestry in Great Britain plus those estimated for eucalypts are given in Table 2.3.

Wood density is also important as it largely determines the calorific value per unit volume (Neilan and Thompson 2008) and eucalypts have denser wood than other species utilised for biomass production over short rotations: SRC willow has a wood density of 0.4 Mg m^{-3} (Nurmi and Hytönen1994), whereas E. nitens grown in Australia on two sites had a density of 0.471 Mg m^{-3} and 0.541 Mg m^{-3} (Greaves et al 1997) and E. gunnii grown in the Midi Pyrenees in France, a density of 0.5 Mg m^{-3} (AFOCEL 2003b).

Eucalypts for short rotation forestry based on current knowledge

The lack of widespread plantings of a range of eucalypt species in the UK makes it difficult to identify species potential across varied site types. However, several sources of information are available to attempt a preliminary characterisation of their biomass potential in relation, particularly, to their cold tolerance. In addition to Evans' (1986) findings, anecdotal guidance on climatic tolerances, comes from Eucalyptus Nurseries (Eucalyptus Nurseries no date), Eucalyptus Passion (Eucalyptus Passion 2009) and Prima Bio (Prima Bio no date). These findings plus notes from Purse (Purse no date, Purse 2009a, Purse 2009b) and personal observations have been used to compile Table 2.4. Neilan and Thompson (2008) have produced a review of the findings from trials in the Republic of Ireland, but some of their findings are applicable only to those parts of the UK with a comparable (mild) climate. The compilation of information presented in Table 2.4 has focused on species that have rapid growth and achieve dimensions appropriate for wood fuel in northern temperate forestry. Species have been categorised by the minimum winter temperatures that they can survive, after hardening, but unseasonal frosts must be considered as they pose a particular risk. Some species have been omitted due to slow growth and/or poor stem form, including E. pauciflora and Eucalyptus perriniana.

Table 2.3: Growth rates and rotations of trees when used in production forestry in Great Britain (FICGB 1998) with estimates of growth of *E. gunnii* and *E. nitens* (Hardcastle 2006) converted from oven dry tonnes to m^3 using a density of 0.5 tonnes per m^3.

Tree species	**Potential yield (m^3 $ha^{-1}yr^{-1}$)**	**Average yield ($m^3ha^{-1}yr^{-1}$)**	**Rotation (years)**
Scots pine (*Pinus sylvestris*)	4-14	9	55-76
Corsican pine (*Pinus nigra* var *maritima*)	6-20	13	45-60
Lodgepole pine (*Pinus contorta*)	4-14	7	50-60
Japanese larch (*Larix kaempferi*)	4-16	9	45-55
Douglas fir (*Pseudotsuga taxifoli*a)	8-24	14	45-60
Norway spruce (*Picea abies*)	6-22	12	50-70
Sitka spruce (*Picea sitchensis*)	6-24	13	40-60
Oak (*Quercus robur/ Quercus petrae*a)	2-8	5	120-160
Beech (*Fagus sylvatica*)	4-10	6	100-130
Ash (*Fraxinus excelsior*)	4-10	5	60-80
Birch (*Betula pendula/ B. pubescens*)	2-10	5	40-60
Eucalyptus gunnii		18	12
Eucalyptus nitens		30	8

Booth and Pryor (1991) describe the climatic requirements of 22 eucalypt species suitable for plantation forestry, six of which can be considered cold-tolerant. Comparing the requirements with the climate of Britain, it is clear that two main constraints exist to planting eucalypts widely; the most important is low temperature and a secondary consideration is adequate soil moisture. Additionally, the importance of such constraints is likely to change in the future as a result of climate change. Evans (1980a) recommends caution when using generalised measures such as minimum temperature data to assess site suitability. He asserts that it is rapid cooling following warm periods that presents the main danger to eucalypts. This is supported by the work of Davidson and Reid (1987) who have shown that unhardened eucalypts can be killed by relatively mild frosts. In addition Purse and

Richardson (2001) note that the most damaging situations arise when polar air masses are over the UK, as the resultant prolonged severe cold is capable of killing even hardened, mature eucalypts. The more common occurrence of radiation frosts tend to kill only unhardened, young trees and affect air temperature close to ground level more. Work linking metabolic activity to temperature of eucalypts by Anekonda et al (1996) also supports the assertion that, in general, using latitude and altitude and broad climatic characters is useful in matching exotic species or origins to site. However, the authors also note that this does not characterise a climate sufficiently and that temperature fluctuations on a monthly or daily time scale are also important and a more sophisticated approach is needed. Even in areas that are sufficiently warm, care should be taken to avoid frost hollows and soils that are waterlogged, as this reduces the resistance of some eucalypts to frost. A further factor determining the influence of climate is the origin of the planting material used with variation observed in cold tolerance between and within provenances of species such as E. gunnii (Evans 1986, Cope, Leslie and Weatherall 2008) and E. nitens (Evans 1986, Tibbits and Hodge 2003).

There are opportunities for the development of hybrid clones as they can provide a more favourable mix of traits than each parent alone (Poke et al 2005) and may offer potential for boosting productivity. Eucalypts suited to the UK climate, such as E. gunnii have been shown to hybridise readily, with most success being with closely related species (Potts, Potts and Cauvin 1987). For E. gunnii, species capable of hybridisation include E. nitens, E. dalrympleana and E. viminalis. Evans (1980a) suggests that a hybrid of E. gunnii and E. nitens might be particularly suited to the needs of British forestry, combining good form, fast growth and cold-tolerance. However, experience has shown that obtaining rootable hybrids from these parents is challenging. Hybrid clones of E. gunnii x E. dalrympleana in France showed excellent growth of around 35 $m^3 ha^{-1} y^{-1}$ at age eight years and continued to grow rapidly thereafter (Neilan and Thompson 2008). However, planting of these hybrids in France ceased due to high mortality following an exceptionally severe frost of -21^{o}C in 1985 (AFOCEL 2006) but trials have started again (Melun 2011). Experience with eucalypt hybrids has shown that crosses do not exhibit hybrid vigour, with F1 offspring tending to show characteristics intermediate with those of their parents (Potts and Dungey 2004). While this can allow attractive aspects of two species to be combined, single species clones might also have potential. For example, clones of particularly cold-tolerant individuals of E. gunnii may extend the suitability of this species to colder locations as individuals have been reported to survive temperatures of below –19^{o}C (Evans 1986).

Table 2.4: The potential and constraints of the eucalypt species showing potential for biomass production under UK conditions. All species are categorised by their hardiness to cold events. (hardiness based on Booker and Evans 1983)

Very hardy – likely to survive long periods of –10 to –14°C and short periods of –18°C

Species	Growth rate & form/ Max height	Potential	Disadvantages
E. gunnii	Fast - 1.5 – 2m height growth per year (Booker and Evans 1983) and above 15m^3 ha^{-1} y^{-1} (Forrest and Moore 2008) Wide range of growth forms (Potts 1983, Potts 1985a) means careful selection of material is necessary. Select forest tree forms and avoid shrubby sub species such as *E. gunnii* ssp *archeri*	One of the most frost tolerant eucalypts, can be established over a wider range of sites than others being suited to sites where Yield Class 10-14 m^3/ha/yr conifers can be grown. Provenances that can tolerate the climate of colder areas of Britain have been identified, such as those from Lake McKenzie in central Tasmania (Evans 1986, Cope, Leslie and Weatherall 2008) and observations show no decline in growth rates with frost tolerance between provenances (Evans 1986). Resistant to waterlogged soils in its natural habitat. Considerable variation in the phenotype of different provenances and sub-species (which is reflected in their frost tolerance (Potts and Reid 1985, Evans 1986, Potts 1985c). Some stands show good form, such as the one planted in 1966 at Glenbranter and form could be improved through selection of provenance and superior individuals. It will coppice successfully and has been used in short rotation coppice trials where productivity was high [Forrest and Moore 2008, Mitchell et al 1993). A light crowned species, allows light to penetrate to the forest floor and results in less impact on ground flora (Hardcastle 2006).	Poor form of many trees, could make transport and processing more costly as a source of biomass. A further disadvantage for this use is a wood that is less dense than some species (Potts 1983). Also high moisture content of wood means that it needs a long period of drying of one year for firewood (Booker and Evans 1983). Evans (1986) stated that it could have potential for pulp but unpredictable grain makes the wood unsuitable for timber. Unlike most eucalypts the leaves are palatable to deer, rabbits and hares and so it is susceptible to browsing (Potts 1983, Purse 2009a).

Hardy – as above but unlikely to survive periods of colder than –16^{o}C

Species	Growth rate & form/ Max height	Potential	Disadvantages
E. glaucescens	Fast - 1.5 – 2m height growth per year (Booker and Evans 1983)	More cold tolerant then *E. nitens* and almost as resistant to frost as *E. gunnii*. Considerable potential for production forestry showing excellent stem form. Observations of block planting at the New Forest showed faster growth than *E. gunnii* and excellent self pruning, characteristics which could make it a timber species (Purse 2009b) Found to be highly unpalatable to deer in a planting in West Sussex in 2007 [Purse no date, Purse 2009b]	Evans (1986) noted that only one origin exhibited sufficient cold tolerance in the Forestry Commission trials to be planted more widely.

Moderately hardy – likely to survive long periods of –6 to –9°C and short ones of – 14°C

Species	Growth rate & form/ Max height	Potential	Disadvantages
E. coccifera	Moderate to fast - 1.0 – 2m height growth per year (Booker and Evans 1983). A recent assessment of a trial at Exeter of trees 29 years old gave a mean annual increment of $9m^3$ ha^{-1} y^{-1} (Leslie, Mencuccini and Perks 2014a)	Observations by Purse (2009a) of trials at Thetford, Glenbranter and an older planting attributed to *Eucalyptus nitida* but probably *E. coccifera* at Bishop's Wood, Truro show promising growth and good stem form.	Slower growing than other species at the Exeter trial (Leslie, Mencuccini and Perks 2014a)
E. dalrympleana	Fast - 1.5 – 2m height growth per year (Booker and Evans 1983).	A close relative of *E. gunnii* which is more frost tolerant than *E. nitens* and exhibits faster growth and better form than *E.gunnii*. Occupies a wide range of altitude (Williams and Potts 1996) Considered suited to alkaline soils(Neilan and Thompson 2008) , and observed growing well on brown earths overlaying limestone pavement at Dalton, Cumbria. Gundal hybrid clones (*E. gunnii* X *E. dalrympleana*) produced in France showed promise, having better form and being less palatable than *E. gunnii* but more cold tolerant than *E. dalrympleana* (Evans 1986)	Self pruning and vigorous when coppiced (Neilan and Thompson 2008)] Gundal clones proved to be less hardy than *E. gunnii* and were abandoned from planting programmes in France (Evans 1986)].
E. delegatensis	Moderate to fast - 1.0 - 2m height growth per year (Booker and Evans 1983).Growth at a trial at Exeter at 29 years old averaged $11m^3$ ha^{-1} y^{-1} with one origin exceeding $30m^3$ ha^{-1} y^{-1} (Leslie,	An important source of wood in Australia for construction timber and pulp (Beadle et al 1995). Good growth but poorer survival in more southerly Forestry Commission trials in Britain (Purse and Richardson 2001) and at a small trial in Cumbria. Exhibits promising growth and survival in the milder climate of Southern Ireland, being faster growing than some origins of *E. gunnii* in a planting at Bree (Neilan and Thompson 2008). Found at a wide range of altitudes (Williams and Potts 1996). Evans (1986) recommends high	Some provenances do not coppice and has a relatively low wood density, which makes it less suited as a species for biomass production (Neilan and Thompson 2008).

	Mencuccini and Perks 2014a)	altitude provenances from New South Wales.	
E. urnigera	Fast - 1.5 – 2m height growth per year (Booker and Evans 1983)	Another close relative to *E. gunnii* and similar in its tolerances (Booker and Evans 1983) However, it has the advantage of being less palatable than *E. gunnii* and often displaying better form. Some trees of this species planted in the UK would appear to be natural hybrids with *E. gunnii* (Purse no date). Considered by Neilan and Thompson (2008) as one of three species with particular potential across a range of sites in Ireland.	Lower productivity than some other eucalypts (Neilan and Thompson 2008)

Less hardy – likely to survive long cold periods of less than –6°C and shorter ones down to –9°C

Species	Growth rate & form/ Max height	Potential	Disadvantages
E. johnstonii	Fast - 1.5 – 2m height growth per year (Booker and Evans 1983).	*E. johnstonii* has shown encouraging growth and survival across a variety of sites in Ireland (Neilan and Thompson 2008). Coppices vigorous but not particularly fast growing as a single-stemmed tree, although exhibits good stem form. Some seed origins seem hardier than *E.nitens* or *E. delegatensis*, being similar to *E. gunnii* and *E. pauciflora* (Evans 1980a), which could make this a suitable species for biomass in Great Britain.	Poor survival of most origins of *E. johnstonii* at a trial at Exeter after 29 years (Leslie, Mencuccini and Perks 2014a)
E. subcrenulata	Fast – 1.5-2m height growth per year (Booker and Evans 1983). Estimated growth of 14m^3 ha^{-1} y^{-1} over 29 years at a trial at Exeter (Leslie, Mencuccini and Perks 2014a)	Evans (1986) described central or southern Tasmanian origins of this species as having the greatest potential for growing high quality timber in the British Isles. Survival of 68% and excellent growth and stem form at a trial at Exeter [unpubl. data].	Planting should be restricted to warmer, western parts of Britain.
E. nitens	Very fast - over 2m height growth per year and potentially over 30m^3 ha^{-1} y^{-1} (Purse and Richardson 2001)	Not particularly frost tolerant, but possibly a "moderately hardy" species, surviving down to -14°C (Booth and Pryor 1991) or -12°C (Neilan and Thompson 2008). There are differences in frost resistance between provenances and those from higher altitude areas in Victoria seem best adapted to the British climate (Evans 1986) and careful matching of this species to site is crucial. It has failed completely in several Forestry Commission trials, such as at Thetford (Bennett and Leslie 2003) and in one in Ireland in 2000 (Neilan and Thompson 2008). Considerable variation in frost tolerance by provenance and individuals within provenance (Tibbits and Hodge 2003). Fast growing, with those at Kilmun Arboretum being possibly the fastest growing tree in Britain (Evans 1980a). Widely planted in countries other than Great Britain, so its silviculture is well-understood. If pruned it can provide sawn timber.	Dense crowns shade out ground vegetation which reduced impact of rain and binds soil, so may not be appropriate under certain circumstances, such as where there is potential for soil erosion. Does not coppice very successfully and known as a shy flower producer, which can make seed supply problematic. A closely related species, *Eucalyptus denticulata* formerly known as the Errinundra provenance of *E. nitens* may have potential, as although slower growing (Beadle et al 1989) it coppices (Purse 2005)

Under future climate scenarios temperatures are predicted to rise across the country with increases of between 1.5 to 3^{o}C in winter and a higher rise of between 2.5 and more than 4.5^{o}C in summer for a medium-high emissions scenario by the 2080s. Rises in temperature will generally be greatest in the South East and least in the North West (DEFRA 2002). While higher overall temperatures should favour the planting of eucalypts, other factors, such as enhanced atmospheric carbon dioxide levels may increase the risk of frost damage in evergreens like eucalypts (Lutze at al 1998) and this has been shown in experiments with E. pauciflora (Woldendorp 2008). This observation is supported by other studies, which have shown that increased atmospheric CO_2 delays acclimation in autumn (Coreys et al. 2006 in Lutze et al 1998) and accelerates the loss of cold-hardiness in spring (Lutze et al 1998). In addition to periods of winter cold, unseasonal frosts can be particularly damaging. Booth and Pryor (1991) note that autumn frosts are likely to be the most damaging type of frosts for eucalypts grown in the UK and damage in these circumstances is also likely to increase with elevated levels of atmospheric CO_2.

The limitation of cold is illustrated through an examination of the climatic conditions suitable for E. gunnii, a very cold tolerant species and E. nitens, one which is less so; E. gunnii is known to withstand freezing temperatures of down to -18^{o}C and E. nitens of -12^{o}C (Sheppard and Cannell 1987, Booth and Pryor 1991). If the extent of areas in Britain that experience -18^{o}C and -12^{o}C minimum temperatures are examined on maps showing 40 year climatic averages from 1960-1999 (Met Office 1999), it is only coastal areas in Britain where absolute minimum temperature did not fall below -12^{o}C. During the same forty year period considerable areas in eastern Scotland and in southern central England exhibit absolute minimum temperatures of below -18^{o}C. This highlight that there are considerably greater risks from damage by cold in planting E. nitens than E. gunnii. Predictions of climate change developed by the UKCIP02 (DEFRA 2002) for a scenario of medium-high emissions show a rise of up to 3^{o}C in mean winter temperatures and greater increase in summer. Increases in maximum temperatures during summer in southern England may be as high as 5^{o}C in a medium emissions scenario (DEFRA 2002). Provided sufficient soil moisture is available, more extensive areas of Britain should become suited to growing eucalypts. Figure 2.4 illustrates changes in accumulated temperature at the threshold temperature above 5^{o}C (AT5) generated with the Ecological Site Classification system (ESC) using UKCIP02 climate change projections for 2050 low emission scenarios.

A further climatic constraint to planting eucalypts is available soil moisture. E. gunnii is adapted to temperate climates with mean annual rainfall of 800-2400 mm and E. nitens of 750-1500 mm (Booth and Pryor 1991). Long term mean annual rainfall of less than 750 mm is experienced over much of eastern England (Met Office no date a) with warm temperatures this results in high soil moisture deficits, which may limit growth. Recent predictions of climate change (DEFRA 2002) show that while overall mean annual rainfall will stay relatively constant a variation in seasonal precipitation is predicted: in summer, during the growing season rainfall will be reduced, while winter rainfall will increase. This summer rainfall reduction is projected to be particularly pronounced in the south east of the England, with this region only receiving around 40% to 50% of current rainfall by the 2080s for the high emissions scenario or 60 to 80% under the low emissions scenario (DEFRA 2002). Increased summer temperatures coupled with a reduction in rainfall will lead to greater moisture deficits. Figure 2.5 generated through ESC using UKCIP02 climate projections shows predicted future moisture deficit in 2050 across Great Britain for high and low emissions scenarios. Yields are likely to be slightly reduced by climate change in these drier areas and caution is warranted regarding planting Eucalyptus on freely draining soils with low moisture retaining capacity.

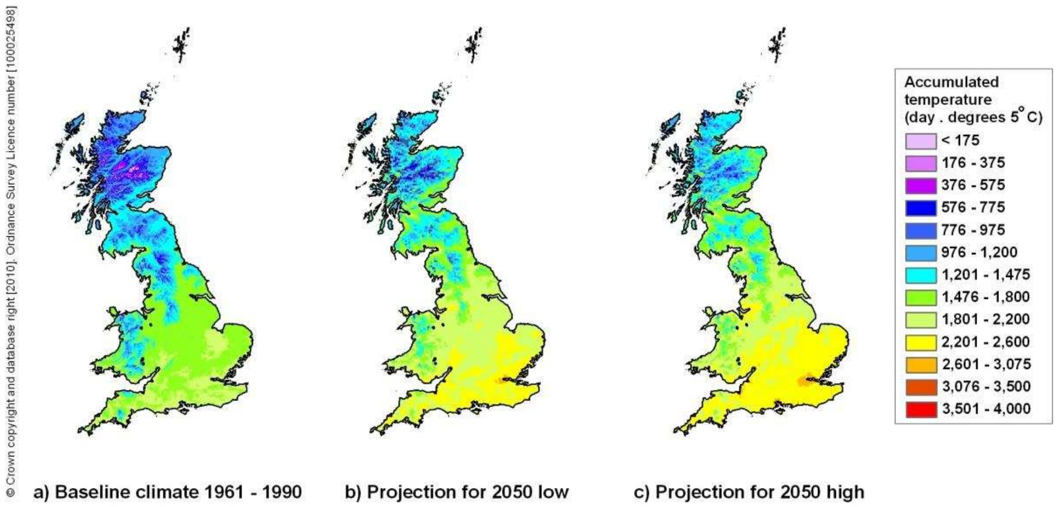

Figure 2.4: Maps of baseline accumulated temperature and projections to 2050 under low and high greenhouse gas emissions based on UKCIP02 predictions (Broadmeadow et al 2009).

Using ESC, provisional areas have been identified that are suitable for planting in Britain with another frost-sensitive, southern tree, Nothofagus nervosa This has been achieved by defining suitable areas from accumulated temperature and moisture deficit data. Areas in Britain with a minimum temperature of -16°C every 50 years were rejected as being unsuitable due to the risk of failure due to cold (Hardcastle 2006). These areas have been identified using work undertaken by Murray, Cannell and Sheppard (1986) on incidence and severity of frost in Britain and it would be worthwhile taking a similar approach to eucalypts.

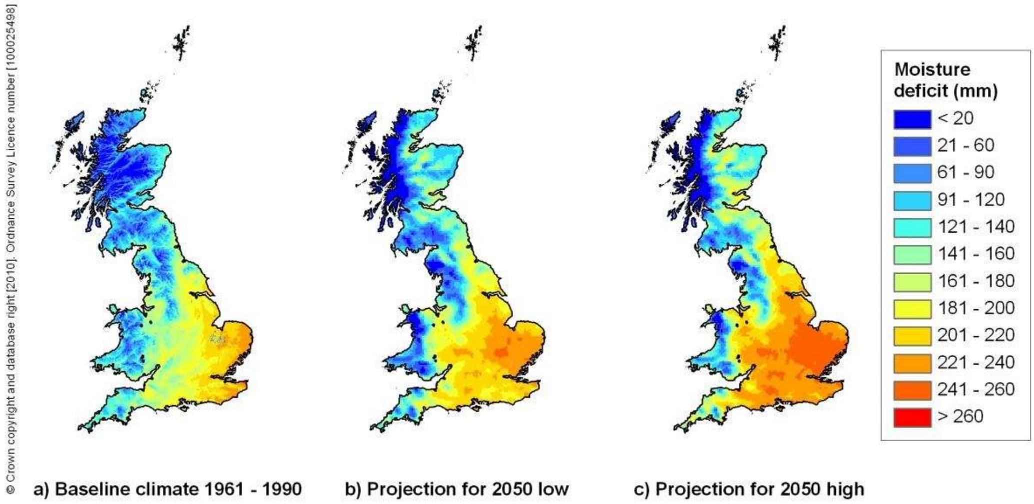

Figure 2.5: Maps of baseline moisture deficit and projections to 2050 under low and high greenhouse gas emissions based on UKCIP02 predictions (Broadmeadow et al 2009).

Impact on the environment

With interest in eucalypt planting rising, there has been increasing concern regarding potential negative environmental impacts. In 1985 a literature review detailed evidence of impacts by eucalypt plantations on water supply, erosion, availability of nutrients, competition with other vegetation and displacement of ecosystems (Poore and Fries 1985). However, these impacts related to specific cases and no generalisations could be made. In France, over 1000 ha of generally small-sized plantations have been established in the Mid-Pyrenees of species that are similar to those suited to the climate of Britain (AFOCEL 2007). While water use was a concern raised in France, eucalypts use water efficiently but consume more water than some tree species due to their higher productivity. Concerns about adverse environmental effects of SRF, including eucalypts, led to a further study focused on the UK (Hardcastle 2006). The study gathered expert opinion and predicted the impacts of SRF with different species and in comparison with other land use, such as pasture, arable cropping and SRC. It was concluded that guidelines should be followed to avoid adverse impacts on soils, hydrology, biodiversity or increase the damage by pests and diseases caused by SRF (Hardcastle 2006).

Of the two eucalypts examined in the study, E. nitens was considered to have greater potential negative impacts on the environment than E. gunnii, particularly in aspects such as biodiversity and hydrology. This is because E. nitens has certain characteristics; the dense shade of its canopy, the slower rate of decomposition of its leaf litter and its fast growth and high water requirements

(Hardcastle 2006). However, Hardcastle (2006) concluded that more widespread planting of eucalypts should be considered, provided certain restrictions be put in place to minimise environmental impacts and that monitoring of activities be carried out by the relevant body.

Socio-political and economic factors

Policy developments directed at energy and land use, including forestry, can influence the uptake of SRF in the UK. Current land use strategy has largely been determined by the policy set by the UK Government and the European Union. To date uptake has been slow, one factor being that SRF does not meet the requirements of Forestry Commission woodland grants nor does it use species that attract grant support under the Energy Crops Scheme. A recent change likely to promote short rotation forestry has arisen from a consultation undertaken by DECC in late 2008, for England and Wales, which proposed dedicated biomass crops should attract additional payments (DEFRA 2006). An incentive now supports power generation from biomass crops, including woody ones such as SRF. Recently, it was announced that heat generated from renewable energy would also attract support by 2011, through RHI (DEFRA 2008)

The Woodfuel Strategy for England is aimed at improving the management of the 60% of woodland that is neglected in order to provide a supply of forest biomass (Forestry Commission England 2007). In Scotland, a study investigating supply of wood fuel recommended, amongst other things, that trials of short rotation forestry be a priority activity (DEFRA 2006). The impacts of short rotation forestry on soils and hydrology, and net site carbon benefit are being assessed in a series of research and demonstration trials of several species, established in 2009 by Forest Research, in both Scotland and England (DEFRA 2008).

Compared with other land uses, biomass forestry has two main attractions in terms of reducing greenhouse gases (St Clair, Hillier and Smith 2008). First, it requires low fossil fuel-derived inputs, such as inorganic fertilisers, pesticides and fuel for farm machinery. Second, the wood grown under SRF provides a substitute source of energy replacing fossil fuels which, with sustainably managed afforestation, could reduce atmospheric CO_2. An additional potential benefit of a change from arable crop production to plantation is increased soil carbon storage. Vanguelova & Pitman (2011) identified that “soil carbon sequestration by SRF is highest on arable soils previously having very low soil carbon….(whilst) impact of SRF on the higher carbon stocks of grassland soils is less certain, although any reductions are likely to be outweighed by the carbon gain in woody biomass". Matthews and Broadmeadow (2009) presented different woodland management scenarios and modelled direct and indirect substitution and carbon sequestration in trees and soil. The amount of CO_2 saved through substitution of fossil fuels was calculated in comparison with a "business as usual" scenario, based on current energy use. Matthews and Broadmeadow (2009) identified that fast growing woody biomass crops on short rotations, such as eucalypt SRF are an attractive option, especially their relatively low cost of emissions abatement and the short term benefits they yield. It is important to acknowledge the limitations of these analyses: reliable data is available for CO_2 balance of conventional forestry, but there is little or no evidence for hardwoods, including eucalypts, under SRF management in the UK. Kerr (2011) lists four areas that make estimating yields imprecise: the shorter rotations, the potential for using 'novel' tree species, the intensive silvicultural approach and the type of sites that would be planted under short rotation forestry. Therefore modelled estimates need to be considered as being preliminary, which highlights the need for more underpinning information. The current 'best estimates' are from Kerr (2011), using published data, which show that over a ten year rotation, yields of 1.5 to 8.2 odt ha^{-1} y^{-1} are possible from E. gunnii and 2.5 to 7.6 odt ha^{-1} y^{-1} from E. glaucescens.

Conclusions

The interest in using biomass as a source of energy has provided a catalyst for the re-examination of the potential role of eucalypts in short rotation forestry in Britain. Their high productivity can provide substantial yields of biomass, reduce greenhouse gas emissions from fossil fuel consumption and can also reduce operational fossil fuel use by replacement of more energy intensive forms of land use. Existing trials and small plantations of eucalypts have shown that there are a limited range of species of eucalypts that can survive and thrive in the relatively low temperatures prevalent in the UK. The limited distribution and extent of plantings make detailed matching of species to site currently imperfect. A sensible approach is, therefore, to attempt to identify species and provenances that will perform well over a wide range of sites and avoid areas that are particularly cold, have low rainfall and for most species, have poor drainage.

Chapter 3 Identification of species and provenances suited to Britain

There has been limited planting of eucalypts in Britain, which makes matching species to site imprecise. The extremely cold winter of 2009 - 2010 (Prior and Kendon 2011, Met Office 2010) highlighted the vulnerability of eucalypts to prolonged sub-zero temperatures. There are however plantings of eucalypts that survived that winter and also previous periods of exceptional cold. A useful, but limited resource are the trials established by Forest Research in the 1980s under a programme directed by Julian Evans. This chapter describes in its first section the results from a set of three trials, testing mainly snow gums (Eucalyptus pauciflora) and in the second section a trial near Exeter testing a range of other cold hardy species. An abridged version of section 3.1 on the trials of snow gums was published in Scottish Forestry, the full citation being:

Leslie, A.D.; Mencuccini, M. and Perks, M. (2013) Growth and survival of provenances of snow gums (Eucalyptus pauciflora) and other hardy eucalypts at three trials in England. Scottish Forestry 67 (2): 30-38.

A modified version of the subsection on the trial at Haldon, Devon, described in section 3.2 was published in the Quarterly Journal of Forestry, the full citation being:

Leslie, A.D. Mencuccini. M. Purse, J. and Perks, M.P. (2014) Results of a species trial of cold tolerant eucalypts in south west England. Quarterly Journal of Forestry 108 (1): 18-27.

This article was improved through the input of Dr John Purse, who provided information on the natural tolerances and characteristics of provenances of species in the E. johnstonii group and helped refine the text and so was included as a co-author.

3.1 Growth and survival of provenances of snow gums (*Eucalyptus pauciflora*) and other hardy eucalypts at three trials in England.

Introduction

The UK Government has made a commitment to increase the proportion of energy from renewable sources from 2.25% in 2008 to 15% in 2020 (DECC 2009). The use of biomass was identified as being central to this transition to a more carbon lean economy (DEFRA 2007b) and woody energy crops will have a role. The Read Report (Read et al. 2009) on the potential contribution of forestry to mitigate climate change, identified short rotation forestry, through the rapid production of woody biomass that will substitute for fossil fuels as being a particularly attractive forestry option for reducing greenhouse gas emissions in the UK.

A genus of trees that has attracted some interest recently as a source of biomass, is Eucalyptus (Hardcastle 2006, Leslie et al. 2012), but only a limited range of the seven hundred species can survive the cold of British winters (Leslie at al. 2012, Evans 1986). The extreme winter of 2009-2010 was the coldest in thirty years and temperatures in parts of the Midlands and south west England dropped to less than -17°C (Prior and Kendon 2011). This was followed by another severe winter in 2010-2011, which was the second coldest (after 2009-2010) since 1985-1986 (Met Office 2011); December temperatures were the lowest for 100 years, being over 5°C lower than the thirty year average (1971-2000) for England. These extreme temperature events have highlighted the importance of selecting trees adapted to the British climate and with cold-hardy eucalypts there seems to be a trade-off between growth rates and hardiness. One of the fastest growing species, Eucalyptus nitens has very rapid growth, with Yield Class estimated at over 30 m^3 ha^{-1} y^{-1} (Purse and Richardson 2001); however it will not survive temperatures of less than -12°C (Evans 1986). The more cold-tolerant eucalypts such as Eucalyptus gunnii have slower growth, attaining rates estimated at between 10-15 m^3 ha^{-1} y^{-1} on a 10-12 year rotation (Evans 1983) up to 25 m^3 ha^{-1} y^{-1} (Purse and Richardson 2001). However, for growth rates, even the slower growing eucalypt species outperform native and naturalised broadleaves and commercial conifers over short rotations, although growth rates in extensive plantations are not known and our knowledge is based on small experimental plots. Kerr and Evans (2011) in a review of the growth of exotic tree species, including two eucalypt species at a spacing experiment, concluded that their growth was rapid but that the mortality in extreme cold was a constraint to their wide-scale adoption.

The Forestry Commission trials of the 1980s represent a useful research resource for continued examination of the potential of eucalypts, although there were problems associated with their establishment, such as weed control (Purse and Richardson 2001). The first set of trials were planted in 1981 and the following winter was one of the coldest in decades, with temperatures at the trials in January 1982, falling to between -7°C and -23°C (Evans 1986), eliminating a number of eucalypt species and origins from consideration for production forestry in Britain. From the results of these trials a second set established in 1985 focused on origins that were considered to be particularly hardy. These included subspecies of the snow gum (Eucalyptus pauciflora), a eucalypt known for its cold-tolerance (Green 1969a) and used in several studies of the effects of cold on eucalypt physiology (e.g., King and Ball 1998). Booth and Pryor (1991) gave a lower limit for survival of E. pauciflora ssp. pauciflora of -14°C, based on observations of the climate in its natural range in Australia In 1985, four trials were established across England to test the growth and survival of origins of E. pauciflora and other species with a high degree of cold-tolerance.

The taxonomy of E. pauciflora has been reviewed several times (e.g. Green 1969b) and the species can be divided into three subspecies; E.pauciflora ssp. pauciflora, E. pauciflora ssp. debeuzevillei and

E. pauciflora ssp. niphophila. This classification is adopted in this article and characteristics of each subspecies are described in Table 3.1.

Table 3.1: Characteristics of subspecies of *Eucalyptus pauciflora*

Subspecies	**Growth form**	**Distribution**
debeuzevillei	A medium or sometimes large tree up to 18m (Green 1969a) Smaller than *E. pauciflora* ssp. *pauciflora* with strongly angled, glaucous and warty buds (Brooker and Kleinig 1990).	Restricted distribution in south eastern New South Wales (Brooker and Kleinig 1990).
niphophila	Differs from *E. pauciflora* ssp. *pauciflora* as is a straggly small tree with a height up to 6m (Green 1969a), has smaller adult leaves and glaucous buds and fruits (Brooker and Kleinig 1990). Multi-stemmed after fire damage, but considered single-stemmed if undamaged (Green 1969a).	Alpine areas (altitude >1500m) in New South Wales and Victoria (Brooker and Kleinig 1990).
pauciflora	Small, medium or occasionally tall woodland or forest tree (Brooker and Kleinig 1990), growing up to a height of 18 m (Green 1969a).	Wider distribution than other subspecies across tablelands and mountain areas in south eastern Queensland, New South Wales, south western Victoria and Tasmania and a small population in south eastern Australia (Brooker and Kleinig 1990).

The objective of this paper was to:

- Identify species that are well adapted to the British climate.
- Identify any origins within species that show superior performance
- Estimate mean annual increments of the better performing origins, using volume functions for cold-tolerant eucalypts.

Only three of the four original sites were re-assessed because of very low survival at the most northerly site.

The intention is that the results from this study will provide further information to underpin the identification of eucalypt origins that can be considered for planting in the UK. Given the poor survival of some species of eucalypts (Harrison 2010) in the severe winter of 2009/2010 across both Scottish and English trials, this is of considerable current interest.

Materials and Methods

Site description

The three trials described form part of a series of four trials planted across England in 1985, the other being at Wark (55° 6' 15"N, 2° 19' 28"E), near Kielder. Thetford is in Norfolk, in the East of England, Chiddingfold is in Sussex, in the South East of England while Torridge is in Devon, in the South West. The three trials are randomised complete block designs with three replications. A description of the trials assessed in this study is shown in Table 3.2 and location and layout maps in Appendix 2.1. The trial at Wark was omitted from this study as survival has proven to be very poor, reflecting the low temperatures and high levels of exposure experienced at that site.

Table 3.2: Site description of two provenance trials of snow gums and hardy eucalypts (Forest Research no date a, Forest Research no date b, Forest Research no date c).

Name/ code of trial	Provenance trial of snow gums and hardy eucalypts, Thetford 233/85	Provenance trial of snow gums and hardy eucalypts, Torridge 38/85	Provenance trial of snow gums and hardy eucalypts, Chiddingfold, Alice Holt H374/85
Location	Thetford, Norfolk, 58° 28'N 15", 0° 38' 57"E	Torridge, Devon, 50°47' 55"N, 4° 14' 39"E	Birchfield Copse, Plaistow 51° 03' 49"N, 0° 35' 19"W
Elevation/ Aspect	15m/ south west	152m/ north west	60m/ south west
Exposure	Open to most directions	Moderately exposed	Open to most directions
Slope	Nearly flat, slight slope to the south west corner.	Gentle	Gentle to south west
Geological formation/ soil	Gipping till over chalk/ well (excessively) drained calcareous brown earth of at least 1m over chalk.	Permian upper carboniferous geology/ Brown gleyed intergrade over culm measures	Weald clay/ clay
Vegetation	Previously Scots pine (*Pinus sylvestris*) felled in 1980.	Used as fields up to ten years prior to planting.	Site of a failed 1976 Western Hemlock (*Tsuga heterophylla*) plantation, mainly birch coppice and broom with windblown stumps of 1926 Norway Spruce (*Picea abies*).

The climate of the three trials was characterised using the Forestry Commission's Ecological Site Classification (ESC) software (Table 3.3). Accumulated temperature above 5°C (AT5) ranges in Great Britain from 0 to 2000 (Pyatt, Ray and Fletcher 2001), so all three sites are warm, while the 'Detailed Aspect Method of Scoring' (DAMS) a measure of wind risk, is low (it ranges from less than 10 in sheltered areas to more than 22 in the exposed highlands) and so the sites are sheltered. Continentality

(CT) varies from 1 to 13 in Britain and represents the variation in temperature over the year and Torridge in the south west of England has a more maritime climate, while Chiddingfold and Thetford are more continental. Moisture deficit (MD) ranges in Great Britain from <20mm in very wet, cold areas to >200 in the hotter areas of South East England, with moderate values at Torridge, and high values for Chiddingfold and Thetford .

Table 3.3: Climatic parameters for Thetford, Torridge and Chiddingfold generated by ESC (Pyatt, Ray and Fletcher 2001).

	AT5	CT	DAMS	MD	Summer Rainfall (mm)	Winter Rainfall (mm)
Thetford	1802.1	10.6	11.6	221.9	308.9	312.2
Torridge	1769.5	7.8	13.0	132.3	478.1	712.5
Chiddingfold	1935.1	10.2	11.4	209.7	351.2	463.8

AT5 = accumulated temperature above 5°C, CT = continentality, DAMS = Detailed Aspect Method of Scoring and MD = moisture deficit.

Winter cold is an important factor in the survival of eucalypts in Britain and the climatic profile from ESC does not show the coldness of the three sites. Table 3.4 provides information on other important climatic variables, such as absolute minimum temperatures and mean frost days. Chiddingfold has the lowest absolute minimum temperature, followed by Thetford and then Torridge.

Thermometers originally on the site at Torridge, showed the lower part of the trial (Block II and III) experiences lower temperatures, by as much as 3°C in winter due to cold air drainage, however the higher part of the trial (Block I) experiences greater exposure. The three trials tested the same 66 origins at Thetford and Chiddingfold and 65 at Torridge (E. viminalis 221 was not planted at Torridge), mainly of E. pauciflora but also including four other species of cold-tolerant eucalypts. Details of the origins are shown in Appendix 3. Two small blocks of E. nitens (94) from Mount St Gwinnear, Victoria were planted at Torridge as a filler. In total, 57 origins of E. pauciflora were tested, comprising 31 origins of E. pauciflora ssp. niphophila, 24 origins of E. pauciflora ssp. pauciflora and two origins of E. pauciflora ssp. debeuzevillei. Line plots were established of ten trees, closely spaced at 1.4 m within lines and around 1.6m between lines, resulting in a stocking density of about 4,464 stems ha^{-1} at Thetford and Torridge. At Chiddingfold the trees were planted at approximately 1.3m within lines and 2m between lines, giving a stocking density of 3,600 stems ha^{-1}.

Table 3.4: Temperature and frost days information for meteorological stations near Thetford, Torridge and Chiddingfold. Data for this table was summarised from daily data from 1985 to 2010 obtained from the MIDAS land surface stations data set (British Atmospheric Data Centre no date).

	Met Station	Mean Min Temp (°C)	Min Temp (°C)	Grass Min (°C)	Days at or below 0°C
Thetford	Cambridge	6.5	-12	-16	43
Torridge	North Wyke	7.1	-11	-14	31
Chiddingfold	Alice Holt	5.4	-14	-19	64

Measurement Protocol

Measurements at the Chiddingfold trial took place in May 2009, when the trees were 24 years old, prior to the cold winters of 2009-2010 and 2010-2011 and at Torridge and Thetford in June 2011 when the trees were 26 years old. Two variables were measured on trees in the trial: diameter at breast height (dbh) and total vertical height. Dbh of all stems of standing trees was measured, while for the more time-consuming measurement of height, three trees were randomly selected from the plot using a list of random numbers generated in Microsoft Excel. If fewer than four trees were present in the plot the heights of all trees were measured. Where trees were leaning they were subjectively categorised as leaning (<15°) or heavily leaning (>15°). Measurements followed the conventions described in Matthews and Mackie (2006). A dbh tape was used to measure stem diameter, while height was assessed using a Hagloff vertex III clinometer or a Lazer Technologies Trupulse clinometer. The layout of the trials was easily discernible as plot marker posts were still in place in most areas.

Volume estimation

Volumes were estimated for trees using a volume function developed for cold-tolerant eucalypts by Shell in South America (Purse and Richardson 2001). This adopted a form factor of 0.35, which was applied to the mean height and mean dbh data. This gave a mean tree volume estimate, which was then multiplied by the mean percentage survival and the stocking density (stems ha^{-1}) in the plots to obtain an estimate of standing volume per hectare for the origins of interest. This in turn was divided by the number of growing seasons to get a mean annual increment (MAI).

Statistical Analysis

The means for plots were used in all the analyses. Basal area was used rather than dbh in the analysis as many of the origins displayed a proportion of multiple stems. However, survival was variable across the trials which, in addition to origin, will have influenced plot basal area.

The original objective, as described in the Trial Experimental Records (Forest Research no date a, Forest Research no date b, Forest Research no date c) was to identify whether there were statistically significant differences among origins and blocks using a two-way ANOVA. This was not possible due to:

Complete mortality of some plots making the experiment unbalanced

Poor survival in many plots resulting in plot means derived from measurements being based on very few trees.

The variables measured not following a normal distribution

For all site-based analysis, irrespective of whether at origin or block level a Shapiro-Wilkes test was used to determine whether the plot means for percentage survival, basal area, number of stems and height were normally distributed. Where distributions of data were significantly different from normal transformation was applied; to survival an arcsine transformation and a natural log transformation to other variables. After this, if the data was normally distributed the equality of variances was tested using a Levene's test. If variances were equal an ANOVA was applied and if differences were significant a Tukey post hoc test was used to determine where these differences originated.

If the data was normally distributed but variances were not equal then a Kruskal Wallis test was used to determine whether differences between the data were significant. Then a post hoc Games Howell test was used to identify differences between either blocks or origins. This test requires normality in the data but not equality of variances.

Where the data was not normally distributed, differences were assessed using a Kruskal Wallis test and Mann Whitney tests were used to identify where the differences occurred. Data were analysed in the IBM Statistics package for the Social Sciences (SPSS) version 15.

Results

Comparison of trials

Overall, median plot survival at the trials was low, at 20% at Torridge, 34% at Thetford and 40% at Chiddingfold (Table 3.5); the origins at the three trials were exposed to a number of severe frost events, including those in their early years of establishment (Forest Research no date a, Forest Research no date b, Forest Research no date c), when they were most vulnerable. At Thetford and Torridge, the two origins of E. camphora showed complete mortality, however, there was low survival of one origin at Chiddingfold. Of the basal area, log basal area, height, survival, arcsine survival and number of stems data only log basal area at Torridge and height at Thetford was normally distributed.

Table 3.5: Median height, plot basal area, survival and number of stems summary for each trial.

	Thetford	Torridge	Chiddingfold*
Height (m)	12.1	9.0	11.5
Plot basal area (m^2)	0.0414	0.0187	0.0200
% plot survival	34	20	40
Number stems/tree	1.695	1.17	1.50

* Data for trees that were 24 years old, other trials trees were 26 years old.

As the data were not normally distributed a Kruskal Wallis test was used to determine whether differences exist between height, basal area, number of stems and survival of the trees at the three trials showed very highly significant differences ($P<0.0001$). (See Appendix 4.1 for statistical supporting data).

In general growth across the trial was greater at Thetford than Torridge whilst surviving origins exhibited a greater tendency to being multi-stemmed at Thetford, which might be the result of more frequent frost damage. The trees at Chiddingfold were measured when two years younger, yet their average size was still larger than those at Torridge.

Thetford results

The data from the Thetford trial were analysed for differences between origins and differences between blocks.

Analysis by origin

Basal area and survival of the species or subspecies is shown in Figure 3.1. Some trends are apparent, i.e. the large basal area but very poor survival of E. stellulata and E. viminalis and the average survival and high basal area of E. perriniana, but there were no obvious differences in terms of basal area and survival in the subspecies of E. pauciflora.

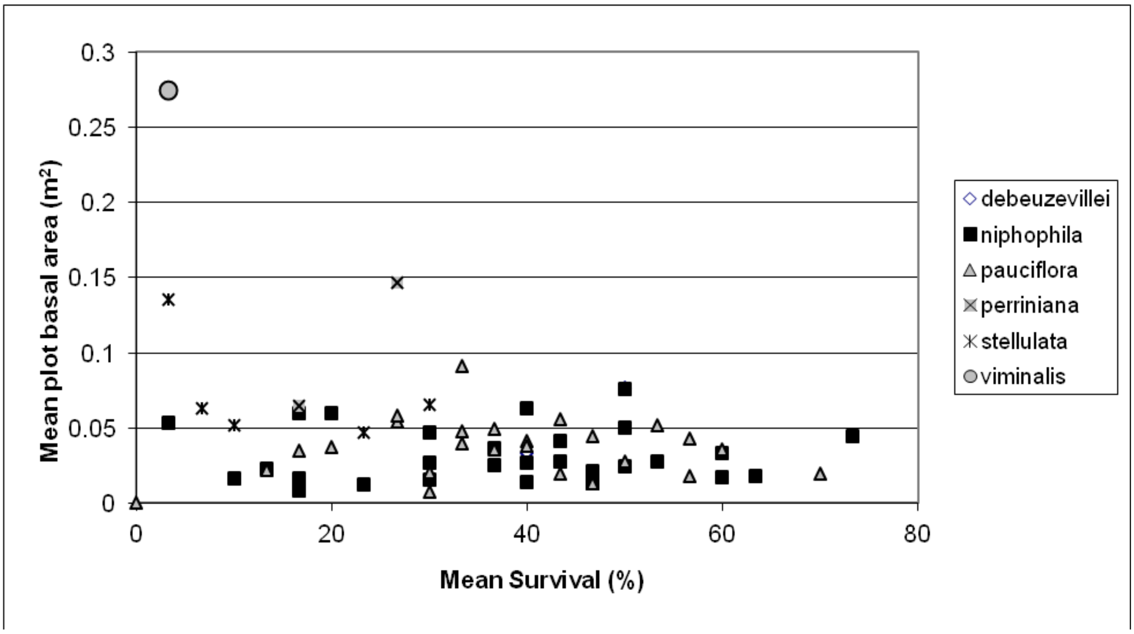

Figure 3.1: Relationship between mean basal area and survival by species or subspecies at Thetford

Differences between the origins in terms of height, number of stems, basal area and survival were tested for significance. There were more than 60 origins and SPSS cannot test heterogeneity of variances for more than 50 origins. As such it was not possible to check this assumption that underpins the use of ANOVA. To test differences across all origins, a non parametic approach (Kruskal Wallis) was adopted that did not require normality or equality of variances. Differences between origins in terms of basal area, number of stems and survival were highly significant ($p<0.01$, See Appendix 4.2 for supporting statistical data). The large number of origins (>50) made comparing all data not possible and so a selection of better performing origins was made by excluding origins with a median plot survival of less than 50% and where there was complete mortality in at least one plot (median rather than mean survival was used as a measure of centrality for survival as it was patchy across the trial and not normally distributed). This reduced the number of origins for testing to 19. Testing the variables for normality showed only height was not significantly different from normal and also exhibited heterogeneity of variances. An ANOVA showed no significant differences in height by origin. For basal area, stems and survival the data were normally distributed but the variances differed even following transformation (natural log for basal area and arcsine for survival). As such non parametric Kruskal Wallis tests were applied. Only basal area differed significantly by origin ($P=0.028$). As basal area was normal but variances differed a Games Howell test was conducted to identify differences in basal area between origins. The basal area of origin 267 (0.0172 m^2) was significantly different from 256 (0.0358 m^2) and 283 (0.0412 m^2). For supporting statistical data see Appendix 4.3.

Analysis by block

The complete data was used to investigate whether there were significant differences between basal area, height, survival and number of stems between blocks. The variables were not normally distributed and so a non-parametric Kruskal Wallis test was used to investigate whether differences existed between blocks. There found to be significant differences in height ($P<0.001$) and stems ($P=0.049$) between blocks. A Mann Whitney U test was used to identify where the differences in height and stems originated and height was found to be significantly different between all three blocks and stems between two blocks. For supporting statistical data see Appendix 4.4.

Torridge results

Analysis by origin

Plotting mean survival and mean plot basal area gave no obvious trends by species, although it highlighted good growth of certain origins of E. pauciflora ssp. niphophila and high basal area but poor survival of an origin of E. stellulata, the result of a few, very large trees (Figure 3.2). As there were more than 60 origins and SPSS cannot test heterogeneity of variances for more than 50 origins it was not possible to check this assumption for ANOVA. To test differences across origins, the non parametic Kruskal Wallis test was used as it did not assume normality or equality of variances. Significant differences were found in height, basal area, survival and number of stems between origins. Significant differences were found between origins in terms of height ($P=0.024$), basal area ($P=0.018$), survival ($P=0.019$) and number of stems ($P=0.005$). See Appendix 4.2 for supporting statistical data.

A smaller number of origins was selected for more detailed analysis being origins with a median plot survival of less than 50% and without all three plots having at least one tree surviving were excluded from the analysis. This left eight origins. LN basal area data exhibited normality and equal variances by origin and an ANOVA and Tukey's test were used to detect significant differences. The plot basal area of E. pauciflora ssp. niphophila origin 239 (0.1042 m^2) was found to differ from that of origins 267 (0.0190 m^2), 271 (0.0163 m^2) and 248 (0.0240 m^2). The statistical supporting information is presented in Appendix 4.5.

For height the data were normal but variances were unequal and for stems and survival the data were not normal so in all cases a Kruskal Wallis test was used. Only for height were significant differences found. The grouping of origin 302 and 239 were significantly different from 248, 276 and 267. Height of origin 240 was different from 271 and 267 (Appendix 4.5 for statistical background).

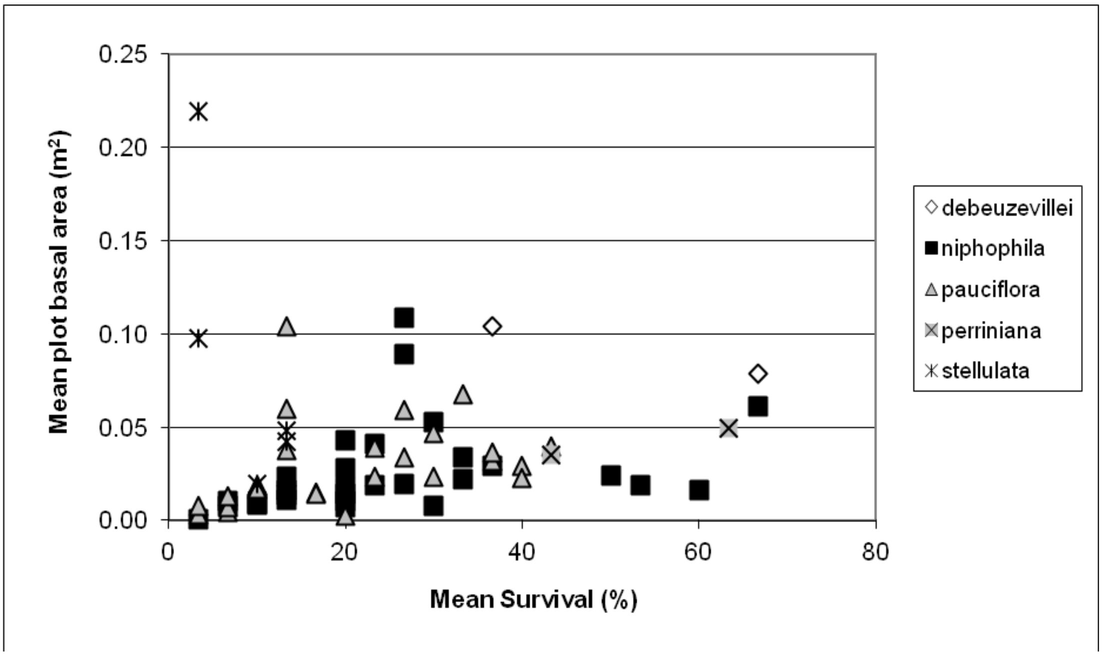

Figure 3.2: Relationship between basal area and survival by species or subspecies at Torridge.

Analysis of data by blocks

Height, LN basal area and stem number were normally distributed and variances were equal so ANOVA was used. Survival was not normally distributed in one block so a Kruskal Wallis test was employed. No significant differences were found in height, basal area, number of stems and survival were found between blocks (Background statistical information can be found in Appendix 4.6).

Chiddingfold results

Analysis by origin

The relationship between mean survival and mean plot basal area showed no obvious trends in growth or survival of species, although one origin of E. perriniana showed particularly high survival and a moderate basal area, whereas three origins of E. stellulata exhibited high basal areas yet poor survival (Figure 3.3). The large number of origins precludes testing of homogeneity of variances and so a Kruskal Wallis test was used to identify differences between origins in terms of basal area, height, survival and numbers of stems. The test showed no significant differences in survival but significant differences in height, basal area and number of stems (P=0.040. 0.019 and 0.0001 respectively). For supporting statistical data see Appendix 4.2.

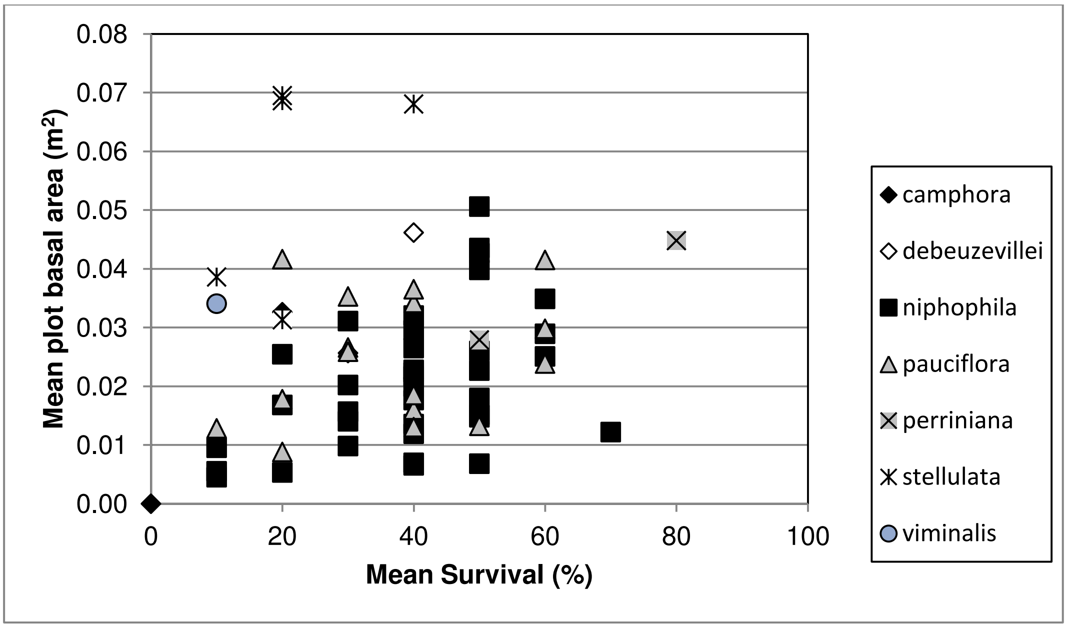

Figure 3.3: Relationship between basal area and survival by species or subspecies at Chiddingfold.

Differences between origins were examined further. Those origins with a median plot survival of more than 50% and with all three plots having at least one tree surviving were used as a dataset. This comprised 14 origins. The statistical analysis is shown in Appendix 4.7. LN transformed basal area conformed to a normal distribution and variances of the origins were equal. An ANOVA was used and significant differences found (P=0.010). This was followed by a Tukey's test to identify specific differences between origins. Basal area of E. pauciflora ssp pauciflora 281(0.0088 m^2) was different from origin E. pauciflora ssp niphophila 243 (0.0506 m^2) and E. perriniana, origin 302 (0.0448 m^2).

Height was normally distributed but variances differed so a non parametric Kruskal Wallis test was used and no significant differences were found between origins. Survival and stems were not normally distributed so a Kruskal Wallis test was applied to these data and only number of stems was significantly different between origins (P=0.007). Mann Whitney test were used to identify where significant differences occurred between origins (Appendix 4.7). These were;

between 283 and all but 303 and 302,

between a grouping of three origins (303, 302 and 289) and all of the following; 294, 291, 287, 278. 273. 288 and 248,

That origin 241 was different from 248 and 291 and origin 273 was different from 248 and 291.

Analysis of data by blocks

Height, basal area, survival and stems were found to be significantly different from normal, including after transformation (Appendix 4.8). A Kruskal Wallis test was used to determine of difference and significant differences were found in height and survival between blocks.

Performance of origins across all three trials

A ranking of plot basal area, (which combines tree size and survival) by origin was undertaken across all three trials. SPSS cannot compute equality of variances across more than 50 cases and this test is required to determine the appropriateness of an ANOVA. As such a non parametric Kruskal Wallis test was used, which does not require data that is normally distributed or has equality of variances (Appendix 4.9). This showed that differences in ranking of basal area by origin was highly significantly different (P=0.0001) across all three trials. Figure 3.4 shows the median basal area per hectare and median survival of those origins in the top quartile by plot basal area. The median basal area per hectare for all origins is also shown as a comparison.

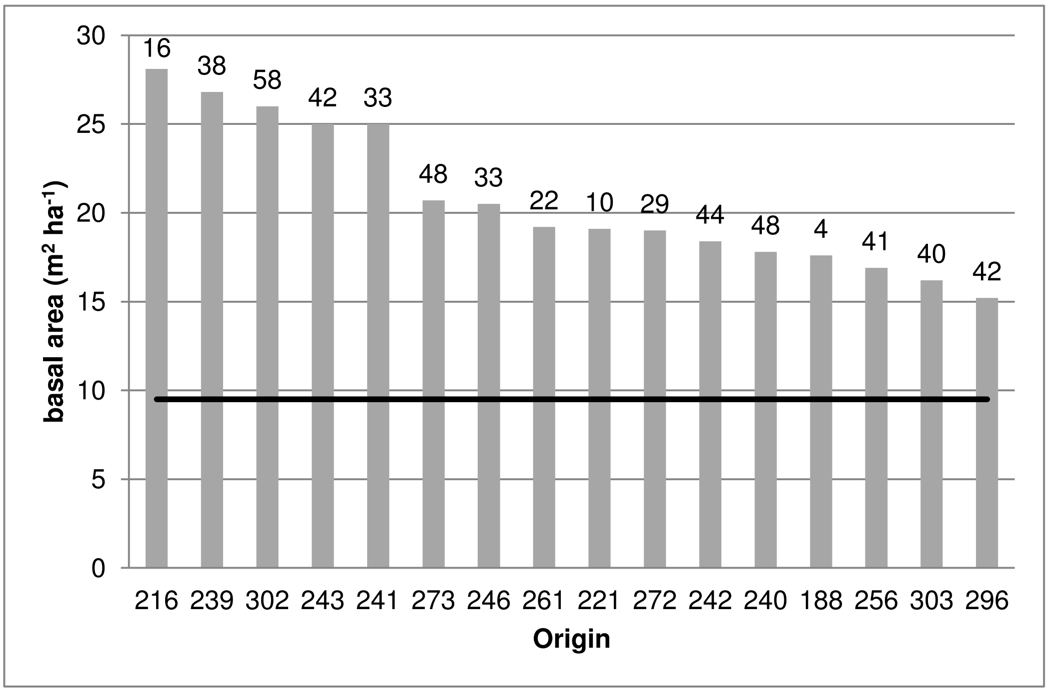

Figure 3.4: Basal area per hectare of the top origins in comparison with the median across the three trials. Median percentage survival is shown by the numbers at the top of each bar.

The survival of some of the origins with highest plot basal area was poor and so origins were identified that had more than 50% survival (Table 3.6).

Table 3.6: Origins with good (>50%) survival in each trial. Those in bold have good median plot survival in two trials and those in bold with underlining good survival across all three trials.

Trial	***E. pauciflora* ssp. *debeuzevillei***	***E. pauciflora* ssp. *niphophila***	***E. pauciflora* ssp. *pauciflora***	***E. perriniana***
Thetford	**239**	243, <u>**248**</u>, 251, 264, **267**, **271**, 276, 277, **283**, **288**, **291**, 292,	256, **273**, **281**, 290, 293, 295, 296	
Torridge	**239**, 240	242, <u>**248**</u>, **267**, **271**		**302, 303**
Chiddingfold		241, 243, <u>**248**</u>, 278, **283**, 287, 288, 289, **291**	**273**, **281**, 294	**302, 303**

Discussion

Deficiencies of the trials

The growth of the trees in these three trials is likely to underestimate their potential. The experimental files show that on the whole weed control was good, but that there were periods early in establishment when the trees faced weed competition. At Chiddingfold the young trees suffered from serious rabbit damage post establishment. The close spacing at the trials has created problems. Competition between trees will have been considerable and it is likely that competition has led to some self-thinning. As early as 1987 the trees at Thetford were already exhibiting crown competition. Instability of the trees has been a problem from the early years of the trials and remains so, possibly exacerbated by the close spacing which may have restricted root development. At Torridge there was considerable windthrow in 2001 (Purse pers comm. 2012) and this was also a problem at Chiddingfold, while there are also patches across the trial at Thetford where many trees have fallen.

Differences between the trials

There are differences in growth and survival between the trials and differences in climate are likely to have a strong influence. Thetford has a more continental climate with colder winters than Torridge (Table 3.4) but also with warmer summers (indicated by the higher accumulated temperature – Table 3.3) and lower summer rainfall, resulting in a higher moisture deficit (Table 3.3) and is less exposed than Torridge (see DAMS score, Table 3.3). Chiddingfold is similar in climate to Thetford but has higher rainfall and lower moisture deficits and experiences lower minimum winter temperatures and for longer periods. The variables generated in ESC and shown in Table 3.3 are based on 1961-1990 climatic data. Since 1990, the climate in the south of England has become appreciably warmer in all seasons, but particularly in spring and winter. Between 1990 and 2004 there was a mean increase in annual temperature of 0.62^{o}C in south west England and Wales and 0.78^{o}C in south central and south eastern England (Perry 2006). This general warming is likely to be beneficial to eucalypts, provided it is not accompanied by the same or greater incidence of occasional extreme periods of cold.

Of the sites, overall survival was best at Chiddingfold, although the assessment was made two years earlier than at the other trials and was before the severe winters of 2009-10 and 2010-11. The different date of assessment makes direct comparison of growth and survival across all three trials difficult. Focussing on differences between Torridge and Thetford, origins tested in the trials exhibited better survival and performance at Thetford but also showed a higher incidence of multiple stems, possibly a response to frost damage. The more mild conditions at Torridge favour less hardy species; E. nitens planted as a filler at Torridge had grown exceptionally well, yet plantings of several origins of E. nitens in the early 1980's at another trial at Thetford had failed completely.

Differences between species and origins

Early observations just after planting already indicated the poor adaptation of some species and origins to the extremes of the British climate. Soon after planting, in June 1985, both sites experienced frost. At Thetford there were five severe ground frosts but this only resulted in minor browning of leaves. During the winter of 1985, at Torridge the temperatures dropped to -7^{o}C at the top of the site and -10^{o}C at the bottom. At both sites, the subspecies of E. pauciflora and origins of E. perriniana remained undamaged but individuals of E. camphora and E. stellulata were badly damaged or dead. At Thetford further cold temperatures were experienced in the winter of 1985, with a -16^{o}C grass minimum and -10^{o}C air minimum temperature (Forest Research no date a).

Since then the trees have been exposed to many unseasonal frosts and abnormally cold winters, including the recent ones of 2009-2010 and 2010-2011. It is clear that the majority of origins tested at the two sites are not sufficiently well adapted to be used in the UK as woody biomass plantation species, showing poor survival and growth. In this assessment there were a small number of origins at the trials that have exhibited good survival and growth, with nineteen origins at Thetford, eight origins at Torridge and fourteen origins at Chiddingfold exhibiting more than 50% mean plot survival and with trees surviving in all three replicates of the trial. The species or subspecies and Forest Research codes for these origins are described and details of the longitude, latitude and altitude of their natural habitat are shown in Appendix 3.1.

Evans (1986) notes that early results from this trial and the other three testing the same origins, showed that there were significant differences in growth and survival between origins. Of the three subspecies of E. pauciflora, E. pauciflora ssp. niphophila was found to be most hardy, followed by E. pauciflora ssp. debeuzevillei and then E. pauciflora ssp. pauciflora. The results from these trials show no such trend. In earlier trials, origins of E. pauciflora ssp. niphophila from Smiggin Hole (1,550 m altitude) and from Smoker's Flat (1,400m altitude) were particularly hardy (Evans 1982). These subspecies were not tested at the three trials in this study. Other origins that showed good cold-tolerance in earlier trials were two from Mount Ginini (Evans 1982), and the one origin tested at these trials (origin 239) showed good survival and superior earlier growth at Torridge. As such, if snow gums are to be planted in future on sites similar to Torridge then this origin should be preferred. However, it did not perform well at Chiddingfold. Why this should be the case is not clear as it performed well at Thetford and Torridge. The only origin of snow gums that has consistently high survival across all three trials was E. pauciflora spp. niphophila (248) originating from an altitude of 1830m at Mount Bogong in Victoria, but rate of growth was disappointing.

An assessment at Torridge and at Thetford at one year old showed origins of E. pauciflora ssp. pauciflora from Currango Plain (origins 255 to 260) to be superior in terms of growth and survival at both trials but this is no longer the case. At Torridge E. pauciflora ssp. niphophila origins from Neengar Plain (origins 283 and 286) were also promising and origin 283 showed good survival at Thetford and good survival and growth at Chiddingfold.

Those that were in the top quartile in the ranking of basal area (Figure 3.4) and which showed consistently good survival across the trials (Table 3.6) were: E. pauciflora ssp. debeuzevillei (239), Mount Ginini; E. pauciflora ssp. niphophila (243) Mount Ginini; E. pauciflora ssp. pauciflora (273), Kiandra; E. perriniana (302), Smiggin Hole and E perriniana (303), Kiandra. From these results that combine growth with survival, origins of E. pauciflora from the high altitude (c1700 m) site at Mount Ginini in the Australian Capital Territories are well adapted to conditions in southern England.

The original aim for testing E. pauciflora in this trial was as a potential timber species (Evans 1986), being a member of the 'ash' group, which contains important timber species such as Eucalyptus fastigata and Eucalyptus fraxinoides. However, the highly variable stem form and the tendency to be multi-stemmed are unlikely to make E. pauciflora suitable under UK conditions. For use as biomass the stem form and whether a tree is multi-stemmed is less important, yet poor form and multi-stems do increase the costs of processing and handling compared with straight single stemmed trees. Some of the individuals within the trial show good stem form and thus there is potential to improve for this trait through selection of superior performing genotypes. However, the results from these experiments show that snow gums are relatively slow growing for eucalypts, although they still compare favourably with other genera. These assumptions are confirmed by the small plots of E.

nitens (origin 94 from Mount St Gwinnear, Victoria) used as a filler at the Torridge trial which have grown considerably faster than the snow gums. This is shown in Table 3.7 which compares the growth of E. pauciflora ssp. debezevillei (239) at Torridge with the results from two plots of 0.01 ha measured in the E. nitens. As the area of E. nitens is relatively small, most of the trees should be considered edge trees and so the growth is likely to be less in a large plantation where between tree competition will be greater. While the growth of the E. nitens is impressive at Torridge, there was no survival of several origins of E. nitens at an earlier trial at Thetford (Bennett and Leslie 2003), highlighting the sensitivity to cold of this species.

Table 3.7: Comparison of growth of *E. nitens* and *E. pauciflora* ssp *debeuzevillei* at 26 years old.

Origin	**Mean height**	**Basal area (m^2 ha^{-1})**	**Volume (m^3 ha^{-1})**	**MAI (m^3 ha^{-1} yr^{-1})**
E. nitens (94)	28	98.4	964	37.0
E. pauciflora ssp. *debeuzevillei* (239)	15.6	46.4*	254	9.7

*Assuming a plot size of 22.4 m^2 or a stocking of 4,464 stems ha^{-1} (ie 1.6m between rows and 1.4 m within rows and a ten tree line plot)

Using the plot data for E. pauciflora ssp. debezevillei origin 239 at Thetford, where growth was poorer for this origin, the standing volume was estimated at 180 m^3 ha^{-1} and the mean annual increment was calculated at 6.9 m^3 ha^{-1} y^{-1}. Using ESC predicted Yield Class for ash (Fraxinus excelsior) and sycamore (Acer pseudoplatanus) were estimated. For ash Yield Class 8 was predicted for both sites and for sycamore a Yield Class of 8 at Torridge and 6 at Thetford. Using a growth model for ash of Yield Class 8 with 1.5 m spacing and intermediate thinning (Forestry Commission 2009), the mean annual increment at age 25 years is 6.3 m^3 ha^{-1} y^{-1}. If biomass is the over-riding objective of planting on these sites using snow gums would be a more productive option than native fuel wood species such as ash. A further study that would be worthwhile, if fuel is the main management objective is a comparison of wood density between snow gums and ash as this is an important attribute for the wood's calorific value. While characteristics such as wood density are important, other attributes such as biodiversity and impact on the landscape must also be considered in any assessment of suitability of a tree species to site.

It is also likely that exotic conifers would be more productive than snow gums over a 25-year rotation. An analysis using a UK decision support tool, EMIS, (Perks et al. 2006) indicated a very limited number of species that would be suitable at Thetford, given the moratorium on planting Corsican pine (Pinus nigra var. laricio), with only European larch (Larix decidua) being suitable. In the west of Britain, the future of this species as a commercial crop is also in question, given the potential impact of Phytophthora ramorum. Yield Class 8 European larch at 25 years old would grow at a rate of around 5.5 m^3 ha^{-1} y^{-1} (Forestry Commission 2009). At Torridge a wider range of conifers can be planted as a productive crop and Sitka spruce (Picea sitchensis) will grow at an estimated Yield Class 20. At 25 years of age Sitka spruce would have an average annual growth rate of approximately 13 m^3 $ha^{-1}y^{-1}$(Forestry Commission 2009), considerably higher than the best of the snow gums.

A species that may have be suitable for wood production on milder sites is E. perriniana, which has shown good survival at Torridge and Chiddingfold but poor survival at Thetford. In the Chiddingfold trial, origin 302 (Smiggin Hole) attained a mean height of 15.7m and dbh of 22.1 over 24 years. Using the Shell Chile volume function (Purse and Richardson 2001), these figures give a mean tree volume of 0.212 m^3 and at the trial stocking of 3,623 stems ha^{-1} and with a percentage survival of 83%, an estimated a standing volume of 638 m^3 ha^{-1} or a MAI of 26 m^3 ha^{-1} y^{-1}. Given the small plots and patchy survival across the trial the volume per hectare and growth per hectare should be viewed with caution but it may be that on certain sites this species may have some potential.

Some of the other species tested at the trials had consistently poor survival, although sometimes the few survivors have grown to large dimensions. A few individuals of one of two origins of E camphora survived only at Chiddingfold, while there was poor survival of the one origin of E. viminalis at Chiddingfold and Thetford. There were individuals of E. stellulata across all three trials, but survival was poor. Growth of some of the remaining individuals, however, was impressive. The poor and patchy survival of these species, even in relatively benign sites like Torridge, makes them unsuitable for production forestry in Britain.

Conclusion

The objectives of the study of the results from the three trials were to:

- Identify species that are well adapted to the British climate.
- Within species identify any origins that show superior performance
- Using volume functions for cold-tolerant eucalypts estimate mean annual increments of the better performing origins.

Most of the origins tested at the two trials are unsuitable for production forestry in Britain exhibiting poor survival and growth in British climatic conditions. There are however a few origins that might have potential as a source of biomass: notably: E. pauciflora ssp. debeuzevillei (239), Mount Ginini; E. pauciflora ssp. niphophila (243) Mount Ginini; E. pauciflora ssp. pauciflora (273), Kiandra; E. perriniana (302), Smiggin Hole and E perriniana (303), Kiandra. One origin that was superior to some of the other origins with high survival at Torridge was E. pauciflora ssp. debeuzevillei (239). While the growth rate was poor compared with many other eucalypts it is greater than that achieved within 25 years by naturalised or native broadleaves, the best origin achieving 10 m^3 ha^{-1} $year^{-1}$ at an age of 25 years at Torridge and around 7 m^3 ha^{-1} $year^{-1}$ at Thetford. The growth and survival of snow gums was better at Thetford and Chiddingfold than Torridge and this might be explained by the lower accumulated temperature at Torridge or the higher DAMS score, indicating more exposure. Tentatively, it is suggested that snow gums perform best when accumulated temperature is above 1800 and DAMS is below 12. The accumulated temperature and DAMS figures, are based on climatic data form 1961-1990 and so these limits should be used only as a rough guide, given the increases in temperature in the UK since 1990 (Perry 2006). One origin, E. pauciflora spp. niphophila (248) from Mount Bogong had greater than 50% survival overall and survival in all replicates across all trials, however, growth was unexceptional.

The impressive growth of filler E. nitens at Torridge illustrates the potential of this species, but the complete failure at an earlier trial at Thetford highlights the importance of identifying the site limits for this species, which are likely to restrict planting to the more maritime sites around Britain. While Thetford has a higher accumulated temperature than Torridge, Torridge has a more maritime climate and experiences less extreme low winter temperatures.

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3.2 Results of a species and provenance trial of cold tolerant eucalypts in south west England

Introduction

In this study the performance of six cold-tolerant eucalypt species was assessed at a research trial established in 1981 near Exeter in south west England. This formed one of a series of experimental Eucalyptus trials established across Great Britain (Evans 1980b p2) with the aim of being able to:

"Evaluate the potential of eucalypts as forest trees throughout Britain"

"Identify the most suitable (if any) provenances of each species"

This trial is of particular interest for two reasons: first it remains in reasonable condition, in contrast to most of the eucalypt trials established during the 1980s, and second it contains multiple origins of five species that could be of importance to production forestry in Britain. Eucalypts have been a focus of recent attention in the UK being fast growing exotic hardwoods which are under consideration for planting for short rotation forestry, a specific niche role in the provision of woody biomass for the generation of electricity and heat (Hardcastle 2006). In addition, some of the species may also have potential as timber species and could provide an alternative, in southern England, for productive exotic conifer species such as Corsican pine (Pinus nigra ssp. laricio (Ait.) Melville) stands of which are being damaged or killed by red band needle blight (Dothistroma septosporum) (Brown and Webber 2008) and Japanese larch (Larix kaempferi Carr.), which are under pathological attack from the fungal pathogen Phytopthora ramorum (Webber et al 2010). However, risks to the successful establishment and growth of eucalypts also exist, primarily due to the poor cold tolerance of the genus. In addition, there are concerns about the impacts on biodiversity should widespread adoption of new exotic plantations of Eucalyptus be considered. Plantings of Eucalyptus nitens (Deane and Maiden) Maiden at a series of DEFRA trials in England and Forestry Commission Scotland trials in Scotland were devastated by the extreme low temperatures experienced during the winter of 2009/ 2010 (Harrison 2010), and again in 2010/11. In a planting in Nottinghamshire of 30 ha of E. nitens and Eucalyptus gunnii, the E. nitens were killed by a long spell of extremely cold weather in the winter of 2010/ 2011. The E. gunnii stems were killed to ground level but many have subsequently coppiced (Woodisse 2011). Therefore, there is a pressing need to identify suitable origins of eucalypts for planting commercially and to refine information on their site tolerances.

The choice of species and seed sources planted at the trial was informed by results of earlier trials of eucalypts in Britain, and by availability of new seed of provenances collected from high altitudes by

CSIRO and a private collector in Australia. The species at the trial originate from temperate, montane parts of Australia and represent both the Symphyomyrtus and Eucalyptus sub-genera. Table 3.8 describes some of the characteristics of the species at the trial.

The aim of the study of which the Exeter trial is a part was to:

1. Identify potential species and origins of eucalypts that could be used in production forestry in Great Britain.
2. Contribute to knowledge of the climatic tolerances of eucalypts in Great Britain.

Materials & Methods

Description of the trial

The trial is located near Chudleigh, Devon, at Haldon Forest (50° 37' 59" N, 3° 34' 56"W) and is situated on a gentle south westerly slope at an altitude of 170 m a.s.l. The soils are fertile brown earths overlying greensands and the site was previously under a stand of 1932 Douglas fir (Pseudotsuga menziesii Mirb. Franco.), Yield Class 16, which was felled due to windthrow damage. The trial was planted in May 1981 in four distinct blocks, each block containing a particular species or species group; block one with E. delegatensis, block two with E. nitida, block three with E. nitens and block four with plots of E, johnstonii and plots of E. subcrenulata together (Appendix 2.2). Within these species blocks each origin is represented in three, randomly located, line plots of nine trees. The details of the origins are provided in Appendix 3.2. Some of the origins were collected from a single mother tree, while others are bulked seed lots from several parents. There is some uncertainty about the species and origin of some of the species at the trial; these aspects are reviewed in the Discussion.

An overview of the climate at the trial, based on 1961 to 1991 climatic data and generated by Forest Research's Ecological Site Classification (ESC) system is shown in Table 3.9. Accumulated temperature above 5^{o}C (AT5) in Great Britain ranges up to 2000 degree days (Pyatt, Ray and Fletcher 2001), so with AT5=1663 degree days, the site is very warm, while the 'Detailed Aspect Method of Scoring' (DAMS) wind risk scale, which ranges from around 3 to 36 in Britain, is 12.6 and can be considered to be low, indicating the site is sheltered (although the previous stand was windthrown). Continentality (CT) uses the Conrad Index which varies from 1 to 13 in Britain and represents the difference between the mean temperature (°C) of the warmest and coldest months modified with respect to site latitude: the trial site has a value of 7.9 and so has a moderately continental climate. Moisture deficit (MD) at 128.3 mm is moderate, the range in Great Britain is from <20mm in very wet, cold areas to >200 mm in the hotter areas of south east England. Moisture Deficit is an index of climatic dryness and also an important factor in determining the Soil Moisture Regime (SMR). It is expressed as the mean maximum accumulated monthly excess of evaporation over rainfall (1961-1990 period). As such, moisture should not be limiting for much of the year. Therefore Chudleigh can be considered a productive site for tree growth. Establishment operations are described in Table 3.10.

The survival within the trial in June 2010 was very patchy, with few trees in the E. delegatensis block, and almost complete mortality in the E. nitens block. Within these areas of poor survival, natural regeneration of other tree species had occurred.

Trial Assessments

In June 2010 height and diameter at breast height were measured, the trees having grown for 28 seasons. Diameter at breast height (cm, dbh) of all stems was assessed. The height of all trees was measured for E. nitida (n=34), E. delegatensis (n=50) and E. nitens (n=4). For the plots within the E. johnstonii/ E. subcrenulata block, where survival was better (at 26% and 62% respectively), Excel generated random numbers were used to select three trees for height measurement per plot. Height was measured using either a hypsometer (Measurement Devices Ltd (UK) Laserace) or a clinometer (Hagloff AB (Sweden) Vertex III).

Statistical Analysis

As an initial analysis, the means were calculated for percentage survival, plot basal area and height. The quadratic mean dbh was also calculated as this is a useful measure of tree size in forestry. Furthermore, a calculation of volume per hectare and mean annual increment was made. Stem volume was calculated using a form factor of 0.35 as described in Purse and Richardson (2001). Plot size was approximately 49 m^2 for nine trees, giving a stocking density equivalent of 1,837 stems ha^{-1}. Stem volume was divided by area to obtain mean plot volume. This was divided by age to obtain MAI.

To examine the effect of altitude of origin on performance the origins were divided into species groups (Table 3.12) and linear regressions performed on mean survival, mean height and mean plot basal area against altitude.

Table 3.8: Notes on the natural habitat and silvicultural characteristics of eucalypt species at the trial. The species attributions are those given in Evans (1980a).

Species (sub-genus)	Natural habitat	Relevant silvicultural ttributes
E. nitida (*Eucalyptus*)	A sub-alpine species endemic to Tasmania that forms an altitudinal cline with *E. coccifera,* which it replaces at lower altitudes (Williams and Potts 1996).	Wide range of intraspecific variation in size and form (EUCLID 2006) although some trees have wonderful form and large dimensions in the wild.
E. delegatensis (*Eucalyptus*)	A widespread species on mountains of NSW and eastern Victoria. Also found throughout Tasmania, occupying a wide altitudinal range~~,~~ from 160m to 1500m. The species is distributed in patches of one to many hundred hectares with most populations being exposed to snow for several months each year (Boland and Moran 1979).	One of the most important timber trees in Australia. It favours well-drained soils on moderate slopes on a range of parent material (Boland and Moran 1979). Timber from New Zealand-grown trees has been used on a modest commercial scale (Barr 1996).
E. johnstonii (*Symphyomyrtus*)	Occurs in south-eastern Tasmania, generally at elevations up to 900m. In the north-west of its distribution, it overlaps with *E. subcrenulata,* and populations with intermediate characteristics occur. (Nicolle 1997)	Growth form largely dictated by habitat and in forest conditions grows into a tall tree (Williams and Potts 1996). Exhibits rapid growth and good survival in trials in Ireland (Neilan and Thompson 2008)
E. nitens (*Symphyomyrtus*)	Montane parts of Victoria and New South Wales. Scattered populations with considerable genetic variation between and within populations (Tibbits and Reid 1987).	Fast growth, known wood properties and silviculture. Possibly the fastest growing tree in Great Britain (Evans 1980a)
E. subcrenulata (*Symphyomyrtus*)	Closely related to *E. johnstonii,* but occurs at higher elevations (to 1100m) in the west and centre of Tasmania (Nicolle 1997)	Highly variable in form and size in the wild. It tends to be a small multi-stemmed tree on exposed sites, but can be a single-stemmed forest tree up to 60m height in sheltered valleys (Nicolle 1997)

Table 3.9: Climatic parameters for Chudleigh generated by ESC for 1961-1990.

AT5	CT	DAMS	MD	Summer Rainfall (mm)	Winter Rainfall (mm)
1662.5	7.9	12.6	128.3	353.1	583.3

AT5 = Accumulated temperature above 5^{o}C, CT = continentality, DAMS = Detailed aspect measurement of scoring, MD = moisture deficit.

Table 3.10: Early establishment operations undertaken at the Chudleigh trial (Forestry Commission no date d).

Date	Operation
07/81	hand weeding and cutting bramble with chemical weeding in near future
09/81	After heavy rain and high winds 60-70 mph trees of *E. nitens* and *E. delegatensis* blew over and were staked up. The instability was due to their heavy, dense crowns with lots of foliage
07/82	Chemical weeding of *E. johnstonii/ E. subrenulata* replacement plots and beat ups. Note in file “My goodness they look nice”.
05/84	*E. nitens* brashed to 2m as bramble growing up the stems.
06/84.	chemical weeding glyphosate at high concentrations due to rampant bramble growth
09/85	107 dead *E. nitens* felled – more likely to be dead before Spring. Also 102 *E. delegatensis* felled which were either dead, windthrown or of poor form.

The blocking of the trial by separating species groups (Appendix 2.2) meant that the trial had to be treated as four separate trials to avoid the problems associated with pseudoreplication (Hurlbert 1984). The layout precluded a statistical comparison across the trial and restricted comparison to within the blocks containing related species groups. These groups were the same as those used in the regression analysis.

Within each of these species groups, the performance at a species or subspecies level was compared. Normality of the data for basal area, height, survival and also the transformed LN basal area, LN height and arcsine survival was tested with a Shapiro-Wilkes test. If the data was normal equality of variances was tested using a Levene’s test. Where the data were normally distributed and also showed equality of variances t-tests assuming equal variances were employed. Where the data did not meet the normality or equality of variance assumptions, Mann Whitney tests were used.

Results

Analysis between & within origins

A summary of the performance of origins at the trial is described in Table 3.11. There are large differences between species and origins in terms of growth and survival.

Table 3.11: Summary of survival, dbh, height, basal area and volume at 28 years old for origins at the trial.

Species	**Origin**	**Mean % Survival**	**Quadratic mean dbh (cm)**	**Mean height (m)**	**Basal area (m^2ha^{-1})**	**Volume (m^3ha^{-1})**	**MAI($m^3ha^{-1}y^{-1}$)**
E. nitida	21	19%	41.1	22.3	45.2	352.7	12.6
E. nitida	23	26%	43.9	23.6	72.1	595.0	21.3
E. nitida	24	11%	32.0	20.6	16.4	118.2	4.2
E. nitida	48	0	0	0	0	0	0
E. nitida	134	7%	32.1	19.2	11.0	73.9	2.6
E. nitida	135	11%	48.7	26.8	38.1	357.4	12.8
E. nitida	136	22%	37.2	19.1	44.4	296.0	10.6
E. nitida	137	30%	30.9	20.2	40.7	288.3	10.3
E. johnstonii	229[1]	7%	28.1	21.6	8.5	64.0	2.3
E. johnstonii	121	22%	26.9	22.3	23.2	181.0	6.5
E. johnstonii	122	30%	24.0	16.0	24.6	138.0	4.9
E. johnstonii	123	19%	29.3	22.7	23.0	182.2	6.5
E. johnstonii	124	22%	31.1	24.5	31.1	266.2	9.5
E. johnstonii	125	56%	25.0	21.6	50.2	379.3	13.5
E. subcrenulata	115	81%	22.4	20.0	59.0	412.8	14.7
E. subcrenulata	116	67%	37.2	20.3	132.9	944.1	33.7
E. subcrenulata	117	44%	30.3	20.7	58.8	426.6	15.2
E. subcrenulata	118	81%	30.8	20.3	111.8	796.1	28.4
E. subcrenulata	119	63%	33.7	25.8	103.0	931.4	33.3
E. subcrenualata	171[2]	37%	28.3	19.7	42.7	294.8	10.5
E. delegatensis	30	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	131	48%	48.3	18.8	162.4	1068.0	38.2
E. delegatensis	132	11%	63.7	17.2	65.1	391.3	14.0
E. delegatensis	133	15%	42.6	23.4	38.8	317.1	11.3
E. delegatensis	228[3]	19%	60.8	20.7	98.9	717.6	25.6
E. delegatensis	149	26%	38.3	19.9	54.9	382.2	13.7
E. delegatensis	150	26%	40.6	21.2	61.6	456.9	16.3
E. delegatensis	151	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	152	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	153	7%	59.9	22.0	38.3	295.2	10.5
E. delegatensis	154	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	155	19%	44.1	18.7	52.0	339.6	12.1
E. delegatensis	156	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	157	4%	41.6	20.0	9.2	64.7	2.3
E. delegatensis	158	11%	66.1	20.8	70.1	508.8	18.2

1. Originally *E. johnstonii* (37), replaced at beat up in 1982, Originally *E. johnstonii* (69) replaced at beat up in 1982, Originally *E. delegatensis* (148), replaced at beat up in 1982

A linear regression was used to investigate the relationship between mean survival, mean basal area and mean height against altitude of origin. In most cases the relationship between height or basal area and altitude of origin was poor (Table 3.12).

The E. delegatensis origins were then separated into E. delegatenis ssp. tasmaniensis, which is found only in Tasmania and E. delegatensis ssp. delegatensis, which is found only on the main part of Australia. There was a significant and positive relationship between basal area of E. delegatensis spp. tasmaniensis and altitude of origin, with a linear relationship explaining over 80% of the variation and being statistically significant.

The origins attributed to E. nitida at the trial were likely to be a mix of E. nitida and E. coccifera (see Discussion). A regression was performed on all origins, with basal area giving a strong but non-significant relationship with altitude. Origins were then separated based on the location at which they were collected, with the origins from the Hartz Mountains (134) and from St Clements (24) being reclassified as E. nitida and the others being considered E. coccifera. Regression analysis was performed on the E. coccifera origins, and there remained a strong but not significant relationship for basal area. There were insufficient data (mean plot values) for statistical analysis of the response of E. nitida at this site. Details of regressions are presented in Appendix 6.1.

Table 3.12: Relationships for linear regressions of mean survival, mean height and mean plot basal area against altitude of origin.

	Mean % survival		**Mean height (m)**		**Mean plot basal area (m^2)**	
	R^2	**p**	**R^2**	**P**	**R^2**	**p**
E. 'nitida'[1]	(+) 0.008	0.829	(+) 0.170	0.358	(+) 0.495	0.078
E. coccifera[2]	(-)0.166	0.423	(-) 0.023	0.807	(+) 0.481	0.194
E. delegatensis	(+) 0.027	0.559	(+) 0.017	0.717	(-) 0.000	0.958
E. delegatensis (t)[3]	(+) 0.234	0.225	(-) 0.132	0.548	(+) 0.824	0.033
E. delegatenis (d)[4]	(+) 0.006	0.867	(+) 0.001	0.957	(-) 0.002	0.944
E. subcrenulata/ E. johnstonii	(+) 0.028	0.601	(-) 0.032	0.577	(+) 0.019	0.670

1 This includes all origins identified as either *E. nitida* or *E.coccifera*. 2 This only includes those origins that are *E. coccifera,* not origins 24 and 134 which are likely to be *E. nitida*. 3 comprises *E. delegatensis* ssp *tasmaniensis*. 4 comprises *E. delegatensis* ssp *delagetensis*.

Analysis between species

An analysis was performed to examine whether differences in survival, basal area and height between origins were statistically significant, combining all plot means for each species. Due to very poor survival, E. nitens was excluded from the analysis. The mean basal area, mean height, mean survival, quadratic mean dbh and estimates of volume and mean annual increment (MAI) for each species are shown in Table 3.13.

The design of the trial, with each species group being replicated in separate blocks (Appendix 2.2) prevented a comparison of performance across all species. The statistical comparison has been conducted within species groups (Table 3.14) and details of statistical tests are presented in Appendix 6.2.

Table 3.13: Mean basal area, mean height, mean survival and quadratic mean dbh by species after 28 growing seasons.

	Mean % Survival	**Quadratic mean dbh (cm)**	**Mean height (m)**	**Mean plot basal area (m^2 ha^{-1})**	**Mean plot volume (m^3 ha^{-1})**	**Mean plot MAI ($m^3 ha^{-1}$ y^{-1})**
E. nitida[1]	4.6	32.0	20.0	13.7	95.9	3.4
E. coccifera[2]	17.9	39.5	21.3	40.3	301.0	10.8
E. delegatensis	15.6	49.3	20.1	43.4	305.3	10.9
E. delegatensis (t)[3]	17.3	51.9	19.2	67.1	452.4	16.2
E. delegatenis (d)[4]	10.4	42.5	19.1	27.3	183.1	6.5
E. subcrenulata	62.2	30.4	21.1	84.7	634.3	21.9
E. johnstonii	26.0	27.4	21.5	26.8	201.8	7.0

1 This comprises origins 24 and 134, identified as *E. nitida*. 2 This comprises origins that are *E. coccifera,* not origins 24 and 134 which are likely to be *E. nitida*. 3 comprises *E. delegatensis* ssp *tasmaniensis*. 4 comprises *E. delegatensis* ssp *delagetensis*.

Basal area

Following a log transformation, mean plot basal area by species was distributed in a way that was not significantly different from normal and the variances across the species were not significantly different and so t-tests were used to determine whether differences existed between the two different groupings of species found in each block. Differences in log mean plot basal area by species were found to not be significant (Table 3.14).

Height

Height was normally distributed and variances were equal so t-tests were used to determine if differences were significant. There were no significant differences between species (Table 3.14).

Survival

Percentage survival even after an arcsine transformation was not normally distributed, and so Mann Whitney tests were used to detect whether there were differences in survival between species and very highly significant differences were found between E. johnstonii and E. subcrenulata. The results of significance are shown in Table 3.14.

Table 3.14. Statistical significance (p value) of differences in basal area, height and percentage survival between species groups in the same block.

	Basal area	Height	Survival
E. 'nitida'[1] *E. coccifera*[2]	0.391	0.311	0.390
E. delegatensis (t)[3] *E. delegatenis (d)*[4]	0.144	0.509	0.611
E. subcrenulata *E. johnstonii*	0.144	0.672	<0.0001

1 This comprises origins 24 and 134, identified as *E. nitida*. 2 This comprises origins that are *E. coccifera,* not origins 24 and 134 which are likely to be *E. nitida*. 3 comprises *E. delegatensis* ssp *tasmaniensis*. 4 comprises *E. delegatensis* ssp *delagetensis*.

Analysis of growth and survival for the origins with high survival

There were twelve origins with consistently good survival across the trial where trees survived in all three replicates. Five E. subcrenulata origins (origins 115, 116, 117, 118, 119) were considered one grouping as they were collected from individual trees from the same location. The remaining origin (origin 171) was treated as a separate group. E. johnstonii origins 122, 123, 124 and 125 were clumped together as they were also single tree collections from the same location. There were two origins (131 and 133) of E.delegatensis, both from Tasmania that met the survival criteria and were treated as separate groupings. The mean basal area, mean height, mean survival and quadratic mean dbh for each species grouping is shown in Table 3.15.

The nature of the divisions in the trial meant comparisons could only be made between origins in the same block, each of which contained related species or subspecies. The statistical analyses are presented in Appendix 6.3.

Basal area

For the two origins of E. delegatenisis basal area and height were normally distributed and had equal variances so a t-test for equal variances was used to examine significance of differences. There were not significant differences between the two origins. For the three groups of origins of E. johnstonii and E. subcrenulata basal area and height were normally distributed and exhibited equality of variances so an ANOVA was appropriate in determining if differences were statistically significant. Basal area was found to be very highly significantly different ($p<0.0001$). A Tukey's test indicated that the group containing origins 115 to 119 of E. subcrenulata was significantly different from the other origins.

Table 3.15: Performance of origins with survival in all three replicates at the trial.

	Mean % Survival	**Quadratic mean dbh (cm)**	**Mean height (m)**	**Mean plot basal area (m^2ha^{-1})**	**Mean plot volume (m^3ha^{-1})**	**Mean plot MAI ($m^3ha^{-1}y^{-1}$)**
E. delegatensis (131)	48.3	48.3	18.8	162.4	1068.4	38.2
E. delegatensis (133)	14.7	42.6	23.4	38.8	317.4	11.3
E. subcrenulata (115, 116, 117. 118. 119)	67.5	31.1	21.4	93.1	697.3	24.9
E. subcrenulata (171)	36.7	28.3	19.7	42.7	294.7	10.5
E. johnstonii (121, 122, 123, 124,125)	31.2	26.7	21.2	32.2	239.1	8.5

Height

For the E. delegatensis and also E. subcrenulata/ E. johnstonii origins, the data were normally distributed and had equal variances and ANOVA showed no statistically significant differences in height between origins of either of the two groups of species.

Survival

There were origins of E. delegatensis and of E. subcrenulata/ E. johnstonii where survival, even after arcsin transformation, was found to be distributed in a way that was significantly different from normal. Applying a Kruskal Wallis test, no significant differences were found in survival between the two E. delegatensis origins. For E. subcrenulata/ E. johnstonii there were very highly significant differences between origins. Mann Whitney tests showed E. subcrenulata origins (115-119) to be significantly different from the others.

Analysis of growth and survival between origins of E. johnstonii

Most of the origins of E. johnstonii at the trial were from the Hartz Mountains in Tasmania (origins 121 to 125). McGowen et al (2001) note that morphological variation in this species at this location is not continuous which suggests there may be considerable differences between the individuals from which seed was collected. To test this possibility, the survival, basal area and height of the five seed lots from the Hartz Mountains were compared. Basal area and height were normally distributed and variances were equal so an ANOVA was conducted. Survival was distributed in a way that was significantly different from normal so a Kruskal Wallis test was used to detect differences between orins. In all cases there were no statistically significant differences in basal area, height or survival between origins. (See Appendix 6.4 for statistical output).

Discussion

This discussion draws upon the results from this assessment of the trial, unpublished historical archive records of the trial and also the performance of the species in trials elsewhere.

In Tasmania, considerable topographic and climatic variation in habitat over short distances has lead to substantial genetic and morphological variation in eucalypts (McGowen et al 2001, Davidson and Reid 1987). Altitude may therefore be considered to have a strong influence on physiological attributes such as cold tolerance and frost resistance. However, the relationship between survival and growth of origins at the trial was found to be poorly related to altitude, except for survival and basal area of E. subcrenulata and E. johnstonii. The findings from this trial may reflect the variation in topography across the natural range of the species tested, for example some origins from lower altitudes may be subject to cold air drainage in frost hollows. The absolute minimum temperature reported ever in Australia of -22^{o}C was in a hollow at intermediate altitude in Tasmania (Davidson and Reid 1985). This is reflected by the distribution of one of the most cold-tolerant eucalypts, Eucalyptus stellulata which dominates, in its natural range, locations where frost hollows occur, rather than at high altitude.

Furthermore, for species that have a wide distribution in Australia, the continentality of climate at the location of origin may be important in determining which provenances are adapted to the maritime climate across the UK. Evans (1982) identified continentality at the location of origin as being a factor likely to influence suitability of eucalypt species to the UK climate. The results of the trial showed that most of the origins tested are not sufficiently well adapted to the climate of south west England for them to be reliably used in UK forestry. However, the growth rate and form of some make them of interest for production of biomass.

Eucalyptus delegatensis and Eucalyptus nitens

Eucalyptus nitens and E. delegatensis exhibited rapid early height growth of approximately 1 m y^{-1}; some individuals were 1.75 m tall in September 1981, 4 months after planting. However, this growth was associated with poor rooting leading to instability, and some trees were staked in the early years. Furthermore, during three cold winters from 1981/82 to 1984/1985 there was considerable mortality of trees of these two species. By 2010, only four individual E. nitens remained out of 351 planted, and the mean survival for E. delegatensis across the trial was only 16%. Observational notes contained within the research experimental file (September 1985) noted that all provenances of E. nitens were damaged in the winter of 1984-1985 when temperatures dropped to -8^{o}C and were below 0°C for extended periods. Those from altitudes of between 1100-1300m in Victoria were described as being least damaged.

Davidson and Reid (1987) in a study of frost tolerance of sub-alpine eucalypts found E. delegatenisis to be susceptible to cold, including from winter frost and spring frost in trials and from observations from natural stands, This relative lack of cold hardiness was borne out from the results from this assessment. In 1985 two subspecies of E. delegatensis were recognised (Boland 1985); E. delegatensis ssp tasmaniensis, found only in Tasmania and E. delegatensis ssp delegatensis, which is found in other parts of Australia. Tasmanian origins appeared to be better adapted to the climate at the trial, exhibiting better growth and survival (Table 3.13), although differences were not statistically significant. Following the cold winter of 1984-1985 continued survival of higher altitude origins was observed, with greatest damage from cold being in low altitude Tasmanian origins. In the most recent assessment, growth was greatest in origins from higher elevations in Tasmania.

Of the origins of E. delegatensis tested, the origin with most consistent survival and also exceptional plot volume in 2010 was seedlot 131 from a single mother tree at 1200 m on Ben Lomond, Tasmania. However, in Evans' (1986) review, this origin was indicated as being only relatively cold-tolerant, while another origin from the same location was highly tolerant. Furthermore, no trees of seedlot 154, which was from 9 mother trees at 1220 m at the same location (Clarke 2012), remained alive in 2010. These findings suggest that there is considerable within-provenance variation for cold-tolerance.

Eucalyptus nitida/Eucalyptus coccifera

E. coccifera was introduced to Britain in 1840 (Benson 1994) and was noted by Davidson and Reid (1987) as being highly cold tolerant, although Martin (1950) in his review of plantings in Great Britain and Northern Ireland describes it as being moderately cold-tolerant. Trial records state that the inclusion of E. nitida in the trial at Exeter and elsewhere was due to the good growth, form and cold tolerance of this species in a single experiment planted in 1953 near Truro, Cornwall, England (Evans 1980a, Evans and Brooker 1981).

The crowns of the trees at the Truro site were killed by a severe winter in 1978-79, with a temperature of -18°C being recorded locally, but the trees subsequently recovered vigorously from stem epicormic buds. The trees also survived the severe and prolonged cold conditions in early 1963. Twelve of these trees still exist in 2012, and all have excellent form. The original seedlot was identified as E. coccifera, originating from a collection made in 1947 at 900m in Cradle Mountain Reserve, Tasmania; taxonomic studies in 1979-80 on the trees at Truro indicated that the correct attribution was E. nitida. At this time, other related seedlots in the Exeter trial were also assigned as E. nitida, though it is unclear whether this was appropriate as the higher altitudes from which some originated are more typically populated with E. coccifera (Nicolle 1997). Those origins attributed to E. nitida have performed poorly compared with those attributed to E. coccifera (Table 3.13).

The poor survival of all seedlots of this taxon, including the very poor survival of trees raised from seed from the Truro trial (seedlot 24), is surprising in light of the performance of the trees at Truro. Over the period 1981-85 assessments indicate that the species had good winter survival and between 1993 and 1995 records show 18 of the E. nitida plots remaining, with approximately 60% stocking. These records also indicate that apart from seedlot 24, the form of the taxon was poor, with many multi-stemmed trees. Thus, the reason for the poor survival in 2010 remains unclear.

Eucalyptus subcrenulata/johnstonii

The species that has performed best at the trial, in terms of a balance between growth and survival, is E. subcrenulata. This forms a cline with the closely related species E. johnstonii and E. vernicosa in Tasmania. In this environment small shrubs of Eucalyptus vernicosa at high altitude are replaced at lower altitudes by small trees of E. subcrenulata, which in turn are replaced by tall trees of E. johnstonii. (McGowen et al. 2001). The hardiness of this species agrees with Benson (1994) who described the species as hardy and capable of tolerating exposure, and Evans (1986) who, from assessment of Forestry Commission trials, considered that this species had potential as a timber tree in south west England.

However, the seed sources of E. subcrenulata and the E. johnstonii used in the trial are atypical of the two species. Mt Cattley, the source of E. subcrenulata seedlots 115-119, lies at the extreme north-west of the limits of natural distribution of this species. The altitude from which the seedlots were collected (720m) is at the lower limit of natural occurrence of this species. The seedlots were single tree collections, and the dimensions of the parent trees (Evans 1983, Appendix 5.1) were large by the standards of the species. By contrast, the E. johnstonii seedlots 121-125 were sourced from trees in the Hartz Mountains, close to the highest elevations at which the species occurs (760-800m), and at the extreme south-eastern limit of distribution of E. subcrenulata. Seedlots 121-125 were also single tree collections, and the parent trees were exceptionally small for E. johnstonii (Evans 1983, Appendix 5.1). This suggests that the parent trees of seedlots 121-125 may have been an intermediate taxon. The lack of any seed capsules characteristic of E. johnstonii under the trees at the Exeter site, and an abundance of capsules characteristic of E. subcrenulata, supports this.

The survival of the origins classified as E. johnstonii was significantly poorer than that of E. subcrenulata, while differences in basal area and height were not significant. It is also noteworthy that the dimensions of the surviving trees attributed to E. johnstonii were substantially greater than those of the parent trees. Early records from the trial indicate that all sources of both species were essentially undamaged by cold winters until 1985, and that the height growth of the two species was similar. An undated Forest Research file note evidently written between 1993 and 1995 records 35 plots containing trees of the two species, with ‘probably over 60%’ survival overall. Thus the seedlots appear to have relatively good cold tolerance. E. johnstonii has performed well in Ireland where it is considered a species with potential (McCarthy 1979, Neilan and Thompson 2008). As such, the reasons for losses occurring between 1995 and 2010 are unclear; mortality of weaker trees through self-thinning is a plausible explanation.

While it is not explicit in the original trial plan, it seems likely that the Mt. Cattley and Hartz Mountains seedlots were deliberately chosen as likely to represent a balance between acceptable growth and acceptable cold tolerance in E. subcrenulata/johnstonii. Furthermore, the use of single tree collections for both sources, coupled with the trial layout used, would now allow for collection of seed from the best trees for further trials and progeny testing. The results presented here suggest that seed sources of E. subcrenulata originating from lower elevations deserve more extensive testing in milder parts of southern and western Britain.

Conclusion

Certain seedlots and individual trees in the trial grew very rapidly over a period that equates to a relatively short rotation and have survived a number of severe winters and thus appear well-adapted to the Exeter site. If such growth could be obtained consistently and on a significant scale, these origins would clearly be of interest for production forestry. The good performance of seedlots from certain single-tree collections strongly indicates that a considerable part of the explanation for this performance is the genotype of the trees concerned. The results of the trial presented here indicate that bulk seed of any provenance of any species examined could not be recommended for larger-scale deployment. As examples, contrasting performance of progeny from single mother trees of E. subcrenulata from the same location on Mt. Cattley, and of seed origins of E. delegatensis from Ben Lomond, indicate the risks of using bulk seed from identified provenances. However, collections in Australia from superior trees from these provenances could provide well-adapted, genetically diverse material for trial plantings in Britain. These trials could later be converted into seed production stands. Parts of the Exeter trial itself could also be used for seed production, as the design has allowed testing of the genetic worth of half sib families.

Vegetative propagation of superior, well adapted individual trees by rooted cuttings could also provide an opportunity to evaluate their genetic worth across a range of sites. This approach has been used very successfully with other eucalyptus species and hybrids elsewhere in the world, and has led to large-scale deployment of clonal selections. Of the species discussed in this paper, a research study indicates that E. coccifera and E. subcrenulata may have good potential for rooting from cuttings (Orme 1983). However, no further work on these species has been undertaken, and based on precedents with other Eucalyptus species and hybrids, a significant programme would be required to identify selections having both good field performance and ease of rooting. It is not clear how such an investment could be justified at this stage.

It is also noteworthy that E. subcrenulata and E. delegatensis have hardly featured in plantings elsewhere in the UK. Further trials with these species would clearly be of interest, especially on sites having a similar climate to that of the Exeter trial. The E. johnstonii from the Hartz Mountains, which may be E. subcrenulata, has shown much poorer performance, along with other origins that were identified as E. johnstonii. The poor performance of E. johnstonii contrasts with experience of the species in Ireland, where it has shown rapid growth and good survival (Neilan and Thompson 2008). One possible explanation of this discrepancy is that the Hartz Mountain source in general, and/or the single mother trees that were the seed source for the Exeter trial, are not typical of the species. The small size of the mother trees (Evans 1983) is consistent with this conclusion. For E. nitens, it is recommended that it only be planted on sites with the mildest of climates in Britain. For E. nitida and E. coccifera, the situation is more complex as evidence exists of the former species having performed well on sites with a harsher climate. Thus they may be worth further investigation, particularly focusing on higher altitude origins of E. coccifera of good form.

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Chapter 4 Comparison of SRF species at Newton Rigg

4.1 Survival, growth, leaf area and phenology of short rotation forestry species at a trial in northern England

Introduction

To compare growth rate of tree species, relative growth rate (RGR) is often applied as it accounts for differences in tree size at establishment. RGR is determined by three characteristics (Poorter et al 2012); unit leaf rate (ULR), specific leaf area (SLA) and leaf mass fraction (LMF) and these variables are described in Table 4.1. Leaf area ratio (LAR) is also a useful variable that combines LMF and SLA, being the ratio between leaf area and total tree weight. LAR has also been shown to strongly influence RGR, particularly on nutrient rich sites (Poorter and Remkes 1990). On such sites, partitioning of biomass prioritises leaves, rather than roots, which are favoured on nutrient poor sites (Poorter and Remkes 1990); such prioritisation is termed the concept of optimal partitioning. This theory states that biomass is allocated to the organ that collects the most limiting resource (McCarthy and Enquist 2007). However, the development of each organ in a tree must rely on the development of others and so there is a high degree of interdependence. Environmental factors therefore have a strong influence on the variables in Table 4.1, for example increased light levels reduce the LMF and increasing soil nutrients increase LMF (Poorter et al 2012).

Table 4.1: Growth factors, definitions and the abbreviations used.

Variable	Abbreviation	Definition	Units
Leaf mass fraction	LMF	Leaf dry mass/ total plant dry mass	$g\ g^{-1}$
Leaf area ratio	LAR	Leaf area/ total plant dry mass	$m^2\ kg^{-1}$
Specific leaf area	SLA	Leaf area/ leaf dry mass	$m^2\ kg^{-1}$
Unit leaf rate	ULR	Increase in plant dry matter/leaf area/ time	$g\ m^{-2}\ d^{-1}$
Relative growth rate	RGR	Increase in plant mass/unit plant mass/ time	$Mg\ g^{-1}\ d^{-1}$

Differences in LMF exist among tree species also, with faster growing trees exhibiting higher LMF (Poorter et al 2012). In terms of differences in LMF between conifers and broadleaves, biomass allocation to leaves is higher in conifers (evergreen) than broadleaves (deciduous) but this is partly because conifers retain leaves for two or more years (Poorter et al 2012). This higher LMF in conifers may therefore be largely because of the lifespan of the leaf rather than higher partitioning of photosynthetic assimilate to leaves (Poorter et al 2012).

Differences in SLA between different groups of trees; deciduous versus evergreen and fast growing versus slow growing followed the same pattern of a higher ratio for conifers, but differences were found to be greater than for LMF in a meta-analysis undertaken by Poorter et al (2009 in Poorter et al 2012). High SLA is a characteristic of plants that have a high RGR, small seed mass and which are likely to be invasive and both RGR and SLA were good predictors of a plant's potential invasiveness. In a study in Hawaii, the faster RGR of successful invasive plants was found to be related to a higher net assimilation rate (NAR) rather than a higher LAR (Pattison et al 1998 in Grotkopp and Rejmanek 2007). This however was contradicted by results from Poorter and Remkes (1990) which identified LAR as being important. In many respects the characteristics of invasive trees would also reflect a species' suitability for SRF where rapid growth and high competitiveness with competing vegetation are attractive attributes. As such, it is likely that those tree species with a high SLA and RGR would be particularly suitable.

The timing of the physiological processes of a tree (i.e. its phenology) in relation to seasonality is important as it can result in frost damage, drought damage or disrupt reproduction (Chuine and Beaubien 2001). The length of growing season has a strong influence on a tree's productivity and differences exist among species, origins and individual trees in terms of their period of dormancy. There is a compromise relating to the period of dormancy; temperate trees must balance the risk from damage by spring and autumnal frost with the benefits derived from the longer period of photosynthetic activity (Basler and Körner 2012). Dormancy is influenced by three factors; chilling, temperature forcing and photoperiod. Of these photoperiod provides the most reliable cue in terms of timing of physiological processes (Basler and Körner 2012).

The relative importance of chilling, forcing and photoperiod differs among tree species (Vitasse et al 2012), but trees can be grouped in terms of their response. The dormancy in pioneer trees is largely determined by temperature, rather than photoperiod. This reflects their opportunistic, more risky, r-selected strategy. In contrast, late successional trees follow a more conservative approach, requiring a longer period of chilling and are highly sensitive to photoperiod (Basler and Korner 2012). Nutrition has also an influence on period of dormancy; tree species with enhanced access to nutrients, including nitrogen fixing trees like alder adopt a higher risk approach to their foliage in a similar way to pioneer trees (Tateno 2003).

Trees and forests have an important role in combating climate change. The Read report (Read et al 2009) examined the contribution that trees and forests can make to mitigating climate change. This study included an economic analysis of several forestry options in terms of the cost of reducing emissions of CO_2. Of these, the potential for high yielding eucalypt short-rotation forestry (SRF) was shown to have the lowest cost of reducing emissions of greenhouse gases. However, Hardcastle's (2006) report on SRF suggested testing a range of hardwood tree species. The work described in this paper involves four inter-related assessments comparing early growth and survival of six tree species at a trial in Cumbria, northern England. The aim of this study was to identify tree species suitable for biomass production in northern England over short rotations and to investigate the factors that contribute to their productivity. Specifically differences between tree species were compared in terms of:

- Early relative height, stem volume and stem biomass;
- Leaf area, LAR and SLA;
- Length of growing season and
- The combination of growing season and leaf area.

Methods and Analysis

The Experiment

A trial adopting a randomised complete-block design was established close to the Newton Rigg Campus of the University of Cumbria (54°40'N, 2°47'W), testing five tree species in six replicates. The species used had been identified in Hardcastle (2006) as being hardwoods with sufficiently rapid growth to be used in SRF, to produce biomass for energy. These comprised, sycamore (Acer pseudoplatanus L.), alder (Alnus glutinosa L.), ash (Fraxinus excelsior L.) and two eucalypts; Eucalyptus gunnii and Eucalyptus nitens. Container-grown seedlings were planted using a "T" notch and established in 60cm tubes. The area was stock-fenced. Native and naturalised species were planted in November 2008, while the eucalypts were planted later, in late April 2009, with the aim of avoiding late spring frosts.

The trial was originally under grass pasture and the soil was a clay loam brown earth and slightly acid (pH6). Bulk density was 0.76 at 0 cm to 15 cm depth and 1.07 at 15 cm to 30 cm depth. Soil nitrogen was 5.45 tonnes ha^{-1} and 4.35 tonnes ha^{-1} at 0 cm to 15 cm and 15 cm to 30 cm depth respectively (Centre for Ecology and Hydrology 2013). A complete-weeding approach was adopted to kill the pasture grasses using a combination of propazymide and glyphosate.

The climate at the trial, characterised using the Forestry Commission's Establishment Management Information System (EMIS) (Perks, Harrison and Bathgate 2006) is shown in Table 4.2. Accumulated temperature above 5°C (AT5), a measure of the warmth of the site achieves a maximum in Great Britain of around 2000 day degrees (°C) over 5°C (Pyatt, Ray and Fletcher 2001), and at Newton Rigg is 1503, so the site is relatively warm. The 'Detailed Aspect Method of Scoring' (DAMS) wind risk scale is an interval scale of measurement, which varies from less than 10 in sheltered areas to more than 22 in the exposed highlands, is 14 and so the site is moderately exposed. Continentality (CT) represents the difference between the mean temperature (°C) of the warmest and coldest months, altered with respect to site latitude. This varies from 1°C to 13°C in Britain and represents the variation in temperature over the year. Newton Rigg, at 6.3 °C is in the middle of this range and so has a moderately continental climate. The range for moisture deficit (MD) in Great Britain is from <20mm in very wet, cold areas to >200 in the hotter, drier areas of south east England, and this site, with a moisture deficit of 148mm experiences only moderate moisture deficits. Other aspects of the climate at the trial were obtained from the weather station at the Newton Rigg campus and are shown in Table 4.2.

Table 4.2: Climate at the trial from the Establishment Management Information System[1] and from 1971 to 2000 average data from the Newton Rigg weather station[2] (Met Office undated a, except for minimum temperature, which is from Met Office undated b)

AT5[1] degrees/yr over 5°C	CT[1]	DAMS[1]	MD[1] (mm)	Summer Rainfall (mm)[1]	Winter Rainfall (mm)[1]	Mean Min Temp (°C)[2]	Min Temp (°C)[2]	Frost days[2]	Mean Max Temp (°C)[2]
1503.4	6.3	14.0	148.2	386.4	396.2	0.4 (Jan)	-14°C	57.6	19.4 (Jul)

AT5 = Accumulated temperature above 5°C, CT=continentality, DAMS = Detailed aspect method of scoring, MD = moisture deficit.

Excluding the eucalypts, species selected for the trial were all classified by EMIS as being "suitable", rather than "very suitable" or "unsuitable" for the site. The predicted Yield Class (YC) for the species was 8 m^3 ha^{-1} $year^{-1}$ for ash, sycamore and birch (Betula pendula) and 6 m^3 ha^{-1} $year^{-1}$ for alder. The limiting site factors identified by EMIS for the species were exposure (DAMS) for alder and birch, soil moisture regime for sycamore and soil nutrient regime for ash. The origin of the trees' seed was relatively close to the trial site, with the exception of the sycamore which originated from the Midlands. When origins were selected for the trial, attention was paid to the standard recommendations available at the time in the UK for the selected species, as detailed in Table 4.3. In general the origins selected were likely to be well adapted to the site. In contrast, the origins of the eucalypts were unlikely to be optimally adapted to the climate, as they were probably sourced from seed stands in Dipton, New Zealand (Purse pers. comm. 2009a), although accurate information on their origin was not available.

Table 4.3: Origins of trees used in the trial and recommendations for the origins.

Species	**Origin**	**Recommendations**
Alder	Zone 108, South west Scotland	Use British provenances[1].
Ash	Zone 108, South west Scotland	Seed stand material or material slightly to the south of planting site[2].
Birch	Zone 202, central to north east Scotland.	Avoid origins from long distances away from the planting site (slightly southern/ eastern locations seems to give more rapid growth)[2].
E. gunnii	Likely to be from a seed stand at Dipton, New Zealand[3]. Original origin unknown.	Origins from Lake McKenzie and Mount Cattley, Tasmania perform particularly well[4,5].
E. nitens	Likely to be from a seed stand at Dipton, New Zealand[3]. Origin Central Victoria	Victoria provenances are most frost hardy[4]
Sycamore	Zone 403, Midlands, England	Most British provenances grow well at most sites. May increase productivity by using origins from sites slightly to the south 0f the planting site[2].

Recommendations from [1]Worrell (1992) [2]Hubert and Cundall (2006), [3]Purse pers. comm. 2009a, [4]Evans (1986), [5]Cope, Leslie and Weatherall (2008)

The design adopted for the trial was a randomised complete block design, which is the most commonly used design in forest experiments (Wright and Andrew 1976). The design is less suitable when testing large numbers of tree populations, as it is difficult to maintain uniformity in blocks; only five species were initially planted at the trial at Newton Rigg in six blocks. Due to difficulties experienced by the authors when assessing other trials using small plots, particularly line plots (Leslie, Mencuccini and Perks 2012), large 10 x 8 tree plots were adopted, with the inner 6 x 8 trees being measured in most cases.

Measurements and overview of analysis for each study

Measurements taken in the studies are described in the five sections below. Statistical analysis used IBM SPSS Statistics v19. Conformity to a normal distribution was tested for variables before and after log transformation (if necessary). If the data were normally distributed variances were tested for heterogeneity. Three approaches were then adopted: (1) If the data were: normal and variances were equal an ANOVA and Tukey's test were applied if differences were significant. (2) If the data were normal and variances were unequal a Kruskal Wallis test was used, followed by either a Games-Howell test or Mann Whitney tests if significant differences were detected. (3) If the data were not normal a Kruskal Wallis test was used, followed by Mann Whitney tests if significant differences were detected.

Study 1: Height growth and survival after the first growing season

Height was measured for all trees at the trial at planting, to provide a baseline and then all trees were measured at the end of the first growing season in November 2010 and then in November 2011 for species that had failed and been replanted. Height only was measured, using a metre rule or height rod rounded down to the nearest centimetre. Relative height growth (RHG) was calculated to account for the differences in height of planting stock between the species. The formula incorporated height at planting (H_1) and height at a subsequent assessment (H_2) thus:

$RHG = (H_2-H_1)/H_1$

After one growing season, the E. nitens and E. gunnii data were divided into quartiles by H_1 and RHG and survival compared by height quartile to investigate the influence of size of transplants on these variables.

Differences in RHG and survival between species, blocks and quartiles were analysed. Conformity of height, RHG and survival data to a normal distribution before and after transformation (if necessary) was tested. If normally distributed, variances were tested for heterogeneity. Appropriate parametric or non-parametric tests were used depending on the outcome.

Study 2: Stem volume and biomass after two growing seasons

After two growing seasons, at the end of 2010, twelve trees of each species were selected randomly, two from each of the six blocks within the experiment and these were used to collect data on stem volume. Height and basal diameter were measured for all trees in November 2010. Height was measured using a height rod, while the root collar diameter was measured to the nearest 0.1 mm for, using a digital vernier gauge and taking the mean of two 90^o measurements. The same measurements were made after the third growing season in November 2011. Stem volumes (V) were calculated using height (h) and diameter (d) and assuming that the tree stems were conical in shape (Table 4.4).

To enable stem weights for the trees to be estimated, wood samples were taken from a different sample of five trees of each species and sections were cut from the base, middle and top of their stems. Volumes of these stem samples were measured using a water displacement method using OHAUS analytical standard scales and a water density of 1 g cm^{-3}. Stem samples were oven dried at a temperature of 80^{o}C for 3 days, until no further loss in weight was observed and then weighed again to obtain dry weight. Specific gravity (SG) was then calculated for the wood samples and SG (g cm^{-3}) and V (cm^3) used to calculate whole-stem dry weight (M) (Table 4.4). Differences in height, diameter and stem volume between species and blocks were investigated.

Table 4.4: Variables calculated, measurements and equations used.

Calculated variable	Measured variables	Equation
Stem volume in cm^3 (V)	Root collar diameter in cm (d), stem height in cm (h)	$V=\pi d^2 \times h/12$
Specific gravity (SG)	Dry weight in g (DW), volume in cm^3 (V)	SG = DW/V
Stem dry weight in g (M)	Root collar diameter in cm (d), stem height in cm (h), stem dry weight in g (SDW), volume in cm^3 (V)	M= V x SG

Study 3: Leaf Area

Leaf area was determined for four of the five species initially planted at the trial, as E. nitens failed completely over the winter of 2009/2010. In September 2010, the crowns of the twelve trees of alder, ash and sycamore selected for stem volume measurement were wrapped in plastic bird netting to trap leaves as they fell. For sycamore the collections of leaves in late October was straightforward as most of the leaves had already been shed but for alder, many leaves had to be carefully removed from the crowns of the sample trees. It was expected that this did not affect the trees' survival and growth as leaf removal occurred at the end of the growing season. For trees with less than fifty leaves all leaves were measured and for those with more than 50 leaves, all leaves were counted and a systematic sample of 50 was taken. For each leaf, length (L) along the mid rib and width (W) at the widest point of the lamina and petiole length (P) was measured to the nearest millimetre. The use of netting to capture leaves proved to be unsuitable as a means of trapping leaves of ash as the compound leaves of ash disintegrated and some of the small leaflets were not trapped by the bird netting. As such, the leaf length and width could not be measured but the leaf stalk (S) without the leaflets, which remained trapped in the netting was measured for each of the leaves.

For E. gunnii, an evergreen species, the method of trapping fallen autumn leaves was not appropriate. For each of the twelve trees, all the leaves were counted, classified as mature or juvenille and 50 leaves were removed from trees in the plot buffers in a systematic way from the bottom to top of the trees to ensure a good spread. Leaves were classified into two types (mature or juvenile leaves) and measurements of L, W and P were taken for each type of leaf.

From the leaves collected a sample of forty new leaves was taken for each tree species across the range of sizes. L, W and P was measured and also S for ash and the leaf area (LA) was then determined using Compu Eye software and an Epson Perfection 1240 flatbed scanner. For E. gunnii forty juvenile leaves and forty mature leaves were measured. For all species, leaves were then dried for 48 hours at a temperature of 70^{o}C and weighed to obtain an oven-dried weight (M) using OHAUS analytical standard scales and following the approach adopted by Verwijst and Wen (1996). As the original ash leaves had disintegrated new ash leaves were collected at the end of the summer of the following year for leaf area and weight determination purposes.

The total leaf area for each tree of the four species was calculated using allometric methods, similar to the approach adoped in other studies (Wargo, 1978; Verwijst and Wen 1996, Ugese, Baiyeri and Mbah 2008, Serdar and Deirsoy 2006). This involved the determination of relationships between measurements of L and W (and S for ash) to leaf area and leaf weight using least squares regression. Best fit functions were selected based on high R^2 and lowest standard error statistics. Best fit relationships were used to estimate the leaf area of each leaf sampled from the twelve trees of each species. For each tree, a mean leaf area was calculated and this was multiplied by the total number of leaves present to obtain an estimate of total leaf area per tree.

For the twelve trees of each species, the results from the leaf area measurements and of the stem weights were used to calculate specific leaf area (SLA) and leaf area ratio (LAR) parameters (Table 4.5). As destructive sampling of the trees was to be avoided, LAR was calculated based on stem dry weight. Aboveground biometrics focussed on non-destructive assessment of stem volume (V) which was estimated and converted to stem dry weight (SDW).

Table 4.5: Variables calculated, measurements taken and equations used.

Calculated variable	Measured variables	Equation
Leaf Area Ratio (LAR)	Total leaf area in m^2 (LA), stem dry weight (SDW) in kg	LAR = LA/SDW
Specific Leaf Area (SLA)	Total leaf area in cm^2 (LA), leaf dry weight(LDW) in kg	SLA=LA/LDW

Differences in LAR and SLA between species and blocks were investigated and parametric or non parametric statistics applied depending on their suitability.

Study 4: Growing season

The same twelve trees of each species used in study 3, were assessed during 2011 to determine the length of growing season of the tree species at the trial. The method adopted elements from a study of leaf development in rowan (Sorbus aucuparia) (Forest Research no date) and one investigating leaf senescence in birch (Betula pendula) (Worrell 2006).

For bud burst, the terminal bud was used to assess leaf development. If the tree was forked, the stage of development of the terminal bud on the fork with the largest diameter was evaluated. When the two forks were equal in diameter then the highest bud was assessed. The development of the bud was scored on a 0-5 scale with 0 for a dormant bud and 5 for full leaf expansion (the scale was 1 to 6 in original study from Forest Research, no date). The stages in the bud burst scoring were as follows:

0. Bud is closed and in a fully dormant winter state
1. Bud is swollen and the bud scales just started to open, however the bud is still vertical
2. Bud scales have separated and the tightly furled leaves are visible. The bud is bent sideways and can appear “hooded”
3. Bud scales are completely separated, leaves are starting to unfurl and separate but the leaflets (pinnae) on each leaf remain still furled. The leaves appear brownish in colour since the underside is predominantly visible.
4. The leaves are elongated and leaflets have started to separate as well. The appearance is now much more green since the topside of the leaves is now visible
5. All leaflets have separated on the lowest two leaves and the shoot is expanding.

The end of the growing season was assessed through a five stage leaf retention score based on a four stage scoring system originally developed by Worrell (2006) (a zero was added for no leaves). As the trees were still relatively small, the assessment was made by estimating the percentage of the combined leaf area of the tree crown which was still green, not yellow or brown or had lost leaves. This was scored in the following categories:

0. No leaves present;
1. One leaf-20% green;
2. 21-40% green;
3. 41-60% green;
4. 61-80% green;
5. 81-100% green.

For ash, sycamore and alder the growing season length was calculated by multiplying the bud development score or the leaf retention score by number of days. This gave a relative measure of photosynthetic duration. For E. gunnii the number of days with a mean temperature of above 5°C based on climatic records from a weather station at the Newton Rigg Campus, University of Cumbria was used to approximate the growing season. Ashton (1975) in a study or Eucalyptus regnans, a species of warmer climates found that growth began when mean temperatures at 1.3 m above the ground reached 5 - 7.5°C. Growth of Eucalyptus pauciflora a cold-tolerant species is known to take place above 5°C (Ball et al 1997). The accumulated temperature was then multiplied by a bud burst score of five, the trees being in full leaf and active.

Study 5: Estimating Growth Potential

To investigate the influence of growing season and leaf area on growth a growth potential index was created by multiplying tree growing season (collected in 2011) by leaf area (collected in 2010). A regression of this index against stem weight in 2010 was used to identify the importance of these factors in combination in influencing growth.

Results

Study 1: Height, RHG and survival after first growing season

Survival by November 2009 ranged from 87% to 97% across the five species and the height of the tallest eucalypts ranged from 1.5m to 2 m at 7 months after planting. RHG was found not to conform to a normal distribution (Appendix 7.1) and the median RHG for the five species after one growing season in November 2009 are shown in Figure 4.1. Alder showed the largest RHG based on planting height, however, in terms of volume growth, the two eucalypt species had much higher volumes, due to increased stem allocation when compared with alder.

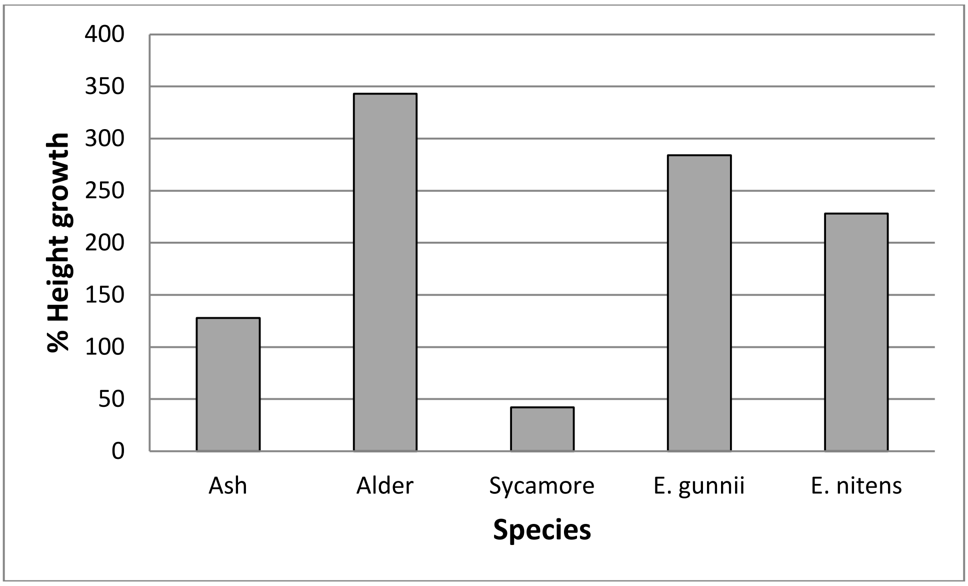

Figure 4.1: Median RHG in height of five species. November 2009 assessment – ash, sycamore and alder 11 months after planting, eucalypts six months after planting (all grown for one growing season).

RHG of E. gunnii and E. nitens showed an inverse relationship against height at planting (data not shown). The RHG data was divided into quartiles based on planting height and highly significant differences ($p<0.0001$) in planting height, RHG and percentage survival were found by quartile (Table 4.6).

Table 4.6: Mean planting height (cm), mean percentage height growth and percentage survival by quartile.

Planting Height Quartile	Planting height (cm)		RHG height (%)		Mean % Survival	
	E. gunnii	*E. nitens*	*E. gunnii*	*E. nitens*	*E. gunnii*	*E. nitens*
1	30a	27a	348a	297a	76.4a	90.3a
2	36b	32b	275b	231b	88.9b	97.2b
3	39c	36c	259b	211b	94.4b	95.8b
4	46d	42d	240b	207b	87.5c	98.6b

Planting height in each quartile for E. gunnii and planting height and percentage height growth for E. nitens were not normally distributed so were investigated using a Kruskal Wallis test and Mann Whitney tests. For E. gunnii percentage height growth data were distributed normally and variances were equally by quartile so an ANOVA and a Tukey's test was performed. Binomial tests were used to investigate differences in survival between the quartiles for both E. gunnii and E. nitens. The statistical supporting data and details of tests performed are shown in Appendix 7.1.

The plots that contained E. nitens and E. gunnii were partly replanted in 2010 and completely replanted in 2011 due to the very poor survival over winter. In 2010 the two species of eucalypt were replanted but in 2011 E. nitens was replaced with birch (Betula pendula). The results after one growing season for the E. nitens and E. gunnii planted in 2010 and the birch and E. gunnii planted in 2011 are shown in Table 4.7.

Table 4.7: Height, height growth and survival after one growing season.

Planting Date	Species	Planting height (cm)	Year 1 Mean height (cm)	Height growth (cm)	RHG height (%)	Survival (%)
7 May 2010	*E. gunnii*	14.7a	62.0a	47.3a	321%a	60.3[1]a
30 April 2010	*E. nitens*	23.3b	69.0b	45.7a	194%b	70.7a
23 May 2011	*E. gunnii*	18.0a	68.5a	52.0a	289%a	82.6a
5 April 2011	Birch	25.0b	98.0b	73.0b	291%a	98.3b

[1] Poor survival may be attributed to the planting stock, which was poor and variable, having been exposed to very cold conditions the preceding winter. Many showed frost damage and had been cut back.

Differences in the data for 2010 for E. nitens and E.gunnii for planting height, year 1 height and mean height growth were found to be normal and variances equal so an ANOVA was used to detect whether differences were significant. Planting height and year 1 height were significantly different between species. For RHG data were not normally distributed and so a Mann Whitney test was applied to determine if differences between E. gunnii and E. nitens were significant and they were very highly significant (For statistical supporting data see Appendix 7.2). Differences in survival between E. gunnii and E. nitens were also examined. Data were found to be normal and have equal variances so a t-test was used, which showed no significant differences (For details of the statistical analysis see Appendix 7.3).

Differences in planting height, year 1 height, height growth and RHG were also investigated by block. Planting height, year 1 height and height growth were normal but planting height alone did not exhibit equality of variances. RHG data were significantly different from normal. As such, ANOVA was used to determine if differences in year 1 height and height growth by block were significantly different. A Kruskal Wallis test was used to determine if differences in planting height and RHG between block were significantly different. No differences were found for any of the variables by block (For statistical supporting data see Appendix 7.2).

Differences in the 2011 data for E.gunnii and birch for planting height, year 1 height, height growth and RHG were tested for normality and all were significantly different from normal. A Kruskal Wallis test was used and all differences between birch and E. gunnii were very highly significant, except RHG which was not significant (Statistical analysis is presented in Appendix 7.4). Survival data was normal and exhibited equality of variances so a t-test was used for percentage survival and significant differences were found (Appendix 7.5 for statistical analysis)

Planting height, year-1 height, height growth and percentage height growth by block for birch and E. gunnii planted in 2011 were not normally distributed before or after a LN transformation. A Kruskal Wallis test was used and highly significant differences were found in all but planting height between blocks (statistical analysis is presented in Appendix 7.4).

Comparison of height growth after three growing seasons

Only the ash, sycamore and alder survived over three growing seasons and poor spraying of herbicide in 2010 resulted in mortality and damage to some of the plots of these species. Results of an assessment in January 2012 are shown in Table 4.8. Trees that had obviously been damaged by the spraying were excluded from further analysis. Data for planting height, year 3 height, height growth and RHG were tested for normality and were significantly different even when a LN transformation was applied as was survival even after an arcsine transformation. A non parametric Kruskal Wallis test was used to determine if differences in planting height, year 3 height, height growth, RHG by species were very highly significant. Mann Whitney tests were then applied to determine whether identify statistical differences between species and results are summarised in Table 4.8 (Statistical analysis is presented in Appendix 7.6). Survival data were normal and variances were equal and an ANOVA showed no significant difference between species (Appendix 7.6)

Study 2: Stem volume and biomass, leaf area and growing season

The twelve trees of each species for the leaf area study were assessed in late 2010 after two growing seasons. By that time all the original E. nitens had died from injury caused during the cold winter of 2009-2010 but 31% of E. gunnii had survived. Volume was calculated for each species after two and three growing seasons for all species, except E. gunnii. The mean data for height, basal stem diameter, and estimated volume are shown in Table 4.9.

Table 4.8 Summary of height (cm), height growth (cm), RHG height percent and percentage survival (of original trees) after the third growing season.

	Ash	Alder	Sycamore
Planting height (cm)	27a	20b	42c
Year 3 height (cm)	122a	186b	128a
Height growth (cm)	93a	169b	86a
RHG (%)	376a	814b	218c
Survival (%)	49a	53a	79a

For the two growing seasons data, height, diameter and stem volume were normally distributed by species. For height the variances were equal and so an ANOVA followed by a Tukey's test were performed. Significant differences were found by species (Table 4.9). For diameter variances were not equal and so for comparison a non parametric approach was used; a Kruskal Wallis test followed by Mann Whitney tests to compare pairs of species and significant differences were found (statistical analysis is presented in Appendix 7.7). For stem volume which was normal but variances differed a Games-Howell test was used to detect significant differences between species (Appendix 7.8). Differences between origins in terms of diameter, height and stem volume are shown in Table 4.9.

The three year growth data for height, diameter and stem volume was also analysed but three species remained, E. gunnii having failed. The natural logarithm (LN) of height and of stem volume and non transformed diameter were normally distributed. LN height and LN volume also exhibited equal variances by species so an ANOVA and Tukey's post hoc test were used. As variances for diameter were not equal by species a Kruskal Wallis and Mann Whitney tests were employed. The significant differences are shown in Table 4.9 and the statistical analysis in Appendix 7.9.

Stem dry weight was calculated by determining specific gravity and stem volumes. Table 4.10 shows the stem volume, specific gravity and stem dry weights. For stem dry weight by species the data were normally distributed but variances were not equal. The specific gravity data were not normally distributed even after a natural logarithm transformation. So a non parametric Kruskal Wallis test with Mann Whitney tests were used to determine if differences in stem dry weight and specific gravity were statistically significant. Significant differences were found and are described in Table 4.10, while the statistical analysis is presented in Appendix 7.10.

Table 4.9: Means for height, stem diameter and volume for each species after two and three growing seasons.

	2 growing seasons			3 growing seasons		
Species	**Height (cm)**	**Diameter (mm)**	**Stem volume (cm^3)**	**Height (cm)**	**Diameter (mm)**	**Stem volume (cm^3)**
Alder	156.9a	27.5a	11.7a	194.5a	43.2a	23.0a
Ash	114.8b	20.7b	6.6b	141.8b	27.8b	9.7*b
E. gunnii	199.4c	35.7*c	19.8c			
Sycamore	130.7ab	15.3b	5.4b	157.7ab	22.1b	9.5b

Table 4.10: Stem volume (V), specific gravity (SG) and calculated stem dry weight (M).

Species	**Stem volume (cm^3)**	**Specific gravity (g/cm^3)**	**Stem dry weight (g)**
Alder	11.7	0.391[1]a	4.575a
Ash	6.6	0.550bc	3.630ab
E. gunnii	19.8	0.548c	10.850c
Sycamore	5.4	0.496dc	2.678b

[1]Alder specific gravity is a median as data were not normally distributed, others presented as means.

To determine leaf area, relationships between L, W and LA and between L, W and LDW were investigated for all species except ash, where the relationship between leaf stalk length and LA and LDW were determined. The best-fit equation was selected by smallest SEE and high R^2. The results from best-fit regressions are described in Table 4.11 and Table 4.12. Statistical output for the models are shown in Appendices 7.11 to 7.15 and 7.17 to 7.21.

Leaf number was compared between species. Data for all species were not normally distributed even after a LN transformation so a non parametric Kruskal Wallis was used, with Mann Whitney tests to determine differences between pairs of species. Very highly significant differences were detected and details are presented in Appendix 7.16 and summarised in Table 4.11.

LA (Table 4.11) and LDW (Table 4.12) were estimated for the twelve trees of each species by applying the regression models to the L x W measurements for all but ash, where they were estimated from leaf stalk length. Neither LA or LDW followed a normal distribution so Kruskal Wallis tests and Mann Whitney tests were used to determine where signifificant differences existed. There were very highly significant differences in LA and LDW and Tables 4.11 and 4.12 summarise them, while details of the statistical analysis can be found in Appendix 7.22.

Table 4.11 Description of the models predicting leaf area where y is mean area of one leaf (LA) in cm^2 and x is L (cm) x W (cm) of the leaf, except for ash where x is leaf stalk length and median leaf area by species. Total tree LA was calculated by multiplying number of leaves by the mean area of one leaf and converted in m^2.

Species	**Number leaves**	**Regression model**	**R^2**	**SEE**	**Median tree LA (m^2)**
Alder	202a	$y=0.325x^{1.102}$	0.941	0.202	0.1919a
Ash	22b	$y = 0.1201x^{2.1891}$	0.707	0.524	0.0627b
Sycamore	25b	$y= 0.532x^{1.021}$	0.964	0.197	0.1856a
E. gunnii (mature)	657c	$y=0.052x^2+0.448x+1.032$	0.967	0.947	0.4999c
E. gunnii (juvenille)		$y=0.7714x^{0.943}$	0.881	0.216	

Table 4.12: Description of the models predicting leaf area where y is LDW of a leaf in grammes and x is L (cm) x W (cm) of the leaf, except for ash where x is leaf stalk length. Whole tree LDW was calculated by multiplying number of leaves by the mean dry weight of a leaf.

Species	**Regression model**	**R^2**	**SEE**	**Median tree LDW (g)**
Alder	$y=0.054+0.001x+0.0000751x^2-0.000000292x^3$	0.967	0.041	21.75a
Ash	$y = 0.004x^2 + 0.005x - 0.029$	0.853	0.187	12.44a
Sycamore	$y=0.007-0.20x$	0.970	0.099	23.63a
E. gunnii (mature)	$y=0.010x+0.001x^2+0.029$	0.981	0.017	100.98b
E. gunnii (juvenille)	$y=0.012x+0.021$	0.932	0.300	

LAR and SLA was calculated for the four tree species and the median values are shown in Figure 4.2. LAR and SLA was tested for normality, before and after a LN transformation and the data were not normally distributed. Kruskall Wallis tests and Mann Whitney tests were applied to the data and highly significant differences were found between species. These are summarised in Figure 4.2 and details can be found in the statistical analysis in Appendix 7:23. The ash LAR was found to be significantly different to all other species while the SLA of all species were significantly different from each another, except for ash and E. gunnii.

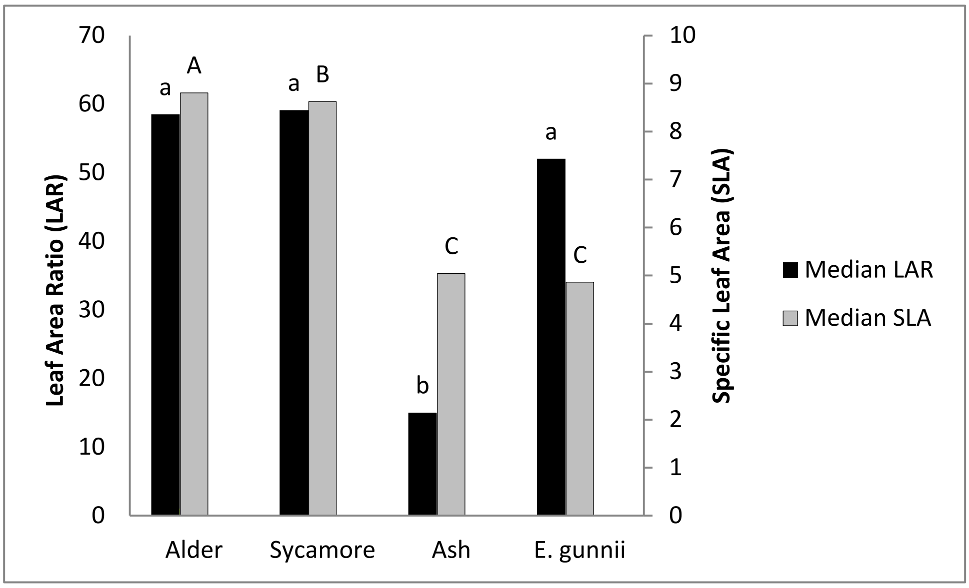

Figure 4.2: Leaf Area Ratios (LAR) and Specific Leaf Areas (SLA) for the four tree species (Different letters above the bars indicates a significant difference).

Growing season

The period of bud burst and senescence for ash, sycamore and alder for 2011 are shown in Figure 4.3. Alder had a longer growing season than the other two species, with an earlier and more rapid bud burst and a later and longer period leading up to complete leaf drop. Ash and sycamore showed a similar response, with sycamore having more rapid bud burst and being slower to drop its leaves.

As E. gunnii was evergreen it was not possible to measure budburst and leaf fall to determine the growing season. The mean growing season index for ash was 868, sycamore was 973 and alder was 1084. A Shapiro Wilkes test test showed that growing season index by species was normally distributed and a Levene's test that variances were equal. ANOVA and a Tukey's test showed that there were very highly significant differences and that the growing season of alder differed from the other two species, ash and sycamore (the statistical analysis is presented in Appendix 7:22).

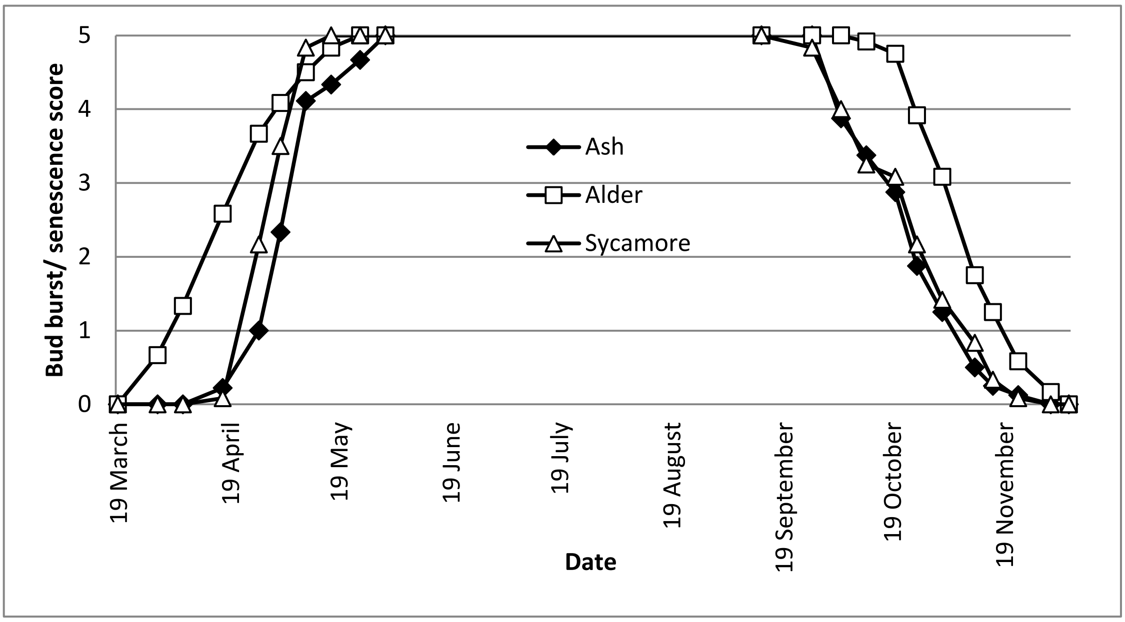

Figure 4.3: Bud burst and leaf retention of ash, sycamore and alder over the growing season of 2011.

Stem dry weight, growing season and leaf area and leaf weight.

A growth potential index was created by multiplying tree growing season index (2011) by LA (2010) and was regressed against calculated stem dry weight (2010). The best fitting function was quadratic (Figure 4.4, R^2 =0.557, standard 1.233, y = $-0.17x^2 + 0.683x + 2.267$) with declining stem dry weight at high growth potentials. The results from other functions fitted to the data are shown in Appendix 7:24.

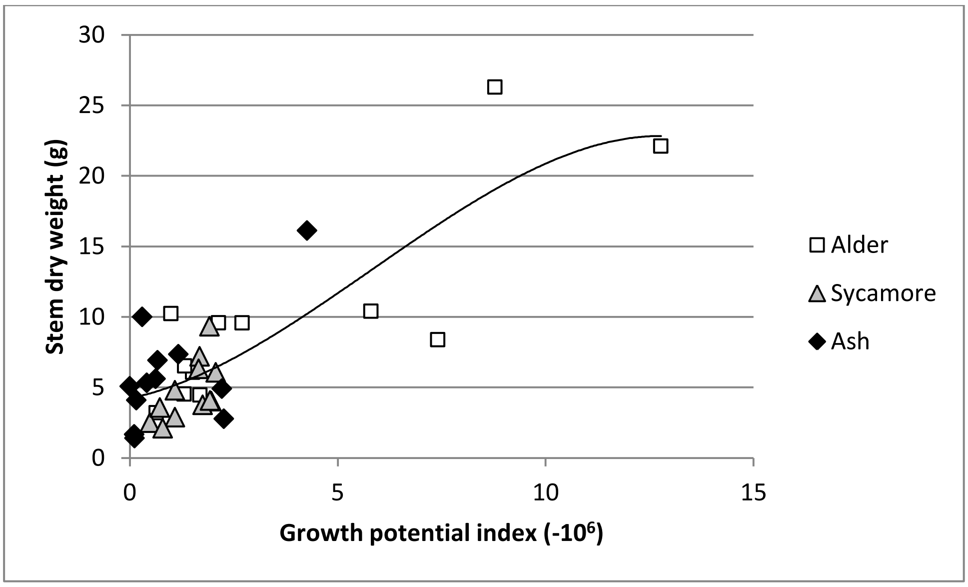

Figure 4.4: Stem dry weight against growth potential index.

Discussion

Study 1: Height growth and survival

The winter of 2009-2010 was the coldest in the UK since 1978-1979 and the UK experienced the coldest December in 100 years (Prior and Kendon 2011). This was followed by another severe winter, which apart from that of 2009-2010, was the coldest since the winter of 1985-1986 (Anon 2011). The extremely cold conditions for two of the three winters experienced by trees at the trial has made the comparison of growth and survival across the years complicated. While the native and naturalised broadleaves were able to cope with these conditions, the eucalypts fared badly, particularly the less cold-tolerant E. nitens which exhibited complete mortality over each of the two severe winters. A further complication is that trees in plots towards the northern and more exposed side of the trial were damaged by spraying of glyphosate for weed control during the summer of 2010. This resulted in both mortality and also long term damage with probable suppression of growth of the surviving trees.

Despite these problems useful results have emerged. Following the first growing season at the trial, alder and the two eucalypts showed rapid growth and good survival (Figure 4.1). Complete pre-planting spraying with propazymide killed the grass and the dead sward helped suppress weed growth. While the trees were only measured for height it was clear from observations of stem thickness that although alder achieved better height growth, the eucalypts produced more biomass. Of the two remaining species, ash exhibited more rapid height growth than the sycamore. Results from the trial suggest that percentage growth of the eucalypts was greatest in the smallest trees, but that survival was also poorer for these trees. The rapid growth of some of the eucalypts in first growing season (some were over 2 m tall), resulted in instability, with some trees requiring additional support. This problem has been noted by other authors (Marriage 1977, Evans 1980a).

Recommendations for size of transplant and optimum planting time are available for most commonly planted tree species in Britain. For production species, mostly conifers, this information has been made accessible to practitioners on-line through the Forestry Commission's Establishment Management Information System (EMIS), as described in Perks, Harrison and Bathgate (2006). Of the species planted, recommendations for silver birch were provided and while the transplant size used (20-40cm cell grown stock) and planting time (from early September to early April) were followed at the trial. The size of transplants and period of planting for the other native and naturalised species appears to be suitable as there was good growth and survival. The timing of planting of eucalypts in the UK is more problematic as there is a trade off between risk of frost damage and the period of growth until the first autumn frosts. Unlike the other broadleaves, the eucalypts were planted when physiologically active. The earliest plantings at the trial in late April were subjected to frosts and later plantings were timed in May. In terms of transplant size, it is recommended that for E. gunnii and E. nitens transplants of 20-30 cm in height be planted, as a compromise between growth and survival and taking stability into account. When some of the larger trees were pulled up, it was found that the root system had spiralled and another recommendation, if planting eucalypts on pasture sites like that at Newton Rigg, is that some form of cultivation be practiced in the planting rows. Evans (1980a) recommends complete cultivation.

Study 2: Stem volume and biomass, leaf area and growing season

Stem volume and biomass and leaf area

After two growing seasons, the largest volumes were achieved with E. gunnii and alder, with the eucalypt producing nearly twice the volume of alder (Table 4.9). Furthermore, these growth data are likely to underestimate the potential of E. gunnii as the trees' roots and foliage were damaged during the hard winter. All the original E. nitens had died from the damage caused in the winter of 2009-2010.

Of the tree species tested at the trial E. gunnii had accumulated the largest leaf area, which would partly explain the fast growth of this species area (Table 4.11). The median leaf area of trees of alder (0.1919 m^2) was significantly different from ash (0.0627 m^2) and E. gunnii (0.4999 m^2), while that of sycamore (0.1856 m^2) was significantly different from E. gunnii (Table 4.11). A study of older trees in the Czech Republic, between 25m and 30m in height showed that oak (Quercus robur) supported a leaf area more than double that of ash, although the species of ash was Fraxinus angustifolia (Kazda et al 2000). At the Newton Rigg trial, while ash had the lowest leaf area, it attained nearly the same stem volume as sycamore and had better RHG.

The leaf area of the trees was measured at the end of the growing season and this may not have fully captured the extent of leaf area over the whole season, as it does not incorporate leaf longevity. There are considerable differences in leaf longevity between temperate tree species; mean leaf lifespan in alder is 90 days and in maples and oaks can be as long as 180 days. (Kikuzawa 1995).

Leaf longevity may explain some of the differences found between species in SLA, the ratio between total leaf area and leaf dry weight. This differed across species, with alder and sycamore being relatively high and E. gunnii and ash being relatively low (with no significant difference between the two). This suggests a greater allocation of resources into each m^2 of leaf in E. gunnii and ash and less resources per unit leaf area in sycamore and alder. Generally there is a positive relationship between leaf mass: leaf area and the longevity of the leaves (Wright and Westoby 2002). Thus some trees invest relatively little in each m^2 of leaf area, allowing rapid build up of canopy, fast cycling of leaves and high initial growth. In contrast other trees invest more heavily in each square metre of leaf area but retain these leaves for longer, resulting in a longer period of return from those leaves (Wright and Westoby 2002).

In terms of SLA, this would suggest that trees which retain their leaves for longer periods will have a lower SLA and those with short leaf longevity have a high SLA. Alder leaves are retained by the tree for a relatively short period (Kikuzawa 1995) and so, as found in this study (Figure 4.2) exhibit a relatively high SLA of (8.8 m^2 kg^{-1}) which would support such a strategy, each leaf being given a relatively low investment of resources. There are no studies of the leaf longevity of E. gunnii, but Whitehead and Beadle (2004) note that in general eucalypt leaves are thick, tough and long-lived, a reflection of their evergreen habit and their association with sites of low soil nutrients and mild winters. A study in Australia found Eucalyptus paniculata leaf lifespan to be 1.09 years and that of Eucalyptus umbra to be 2.06 years (Wright and Westoby 2002) but Laclau et al (2009), studying Eucalyptus grandis in Brazil found unfertilised trees in plantation retained their leaves for 111 days. The relatively low SLA (4.9 m^2 kg^{-1}) of E. gunnii (Figure 4.2) suggests a relatively long leaf lifespan. Ash also exhibited a low SLA and a study by Alberti et al (2005) of older trees also found a low SLA for ash, compared with Wych elm (Ulmus glabra). Another characteristic of trees with high SLA, such as the alder and sycamore in this study, is that they tend to exhibit high photosynthetic nitrogen use efficiencies, whereas trees with a low SLA adopt a different strategy; absorbing a greater proportion of the light available through a higher chlorophyll content in the leaves (Poorter and Evans 1998).

High wood density is an attractive trait in a tree used for biomass as it results in a higher weight for a particular volume, reducing transport costs. There were statistically significant differences in specific gravity, with alder having a particularly low density (Table 4.10), although this is low, compared with the 0.540 t m^{-3} cited by Claessens (2005 in Claessens et al 2011), perhaps due to the young age of the trees. The specific gravity of ash was similar (0.550 as opposed to 0.560 t m^{-3}) to that found in larger trees from Italy (Alberti et al 2005) and that of E. gunnii was similar (0.548 as opposed to 0.500 t m^{-3}) to that found in French plantations (AFOCEL 2003a).

The mean or median specific gravity was applied to the volumes enabling LAR (using stem weight rather than the conventional whole tree weight) to be calculated. This was compared by species and significant differences were found between ash and all other species ($p<0.001$ for all but E. gunnii, where significance was $p<0.0001$). Therefore ash supports a smaller leaf area per unit stem weight than sycamore, alder and E. gunnii.

Growing season

Phenology of temperate trees is determined by temperature and photoperiod, with the importance of each of these factors varying with tree species (Basler and Körner 2012, Vitasse et al 2012,). This study used visual assessment of budburst, which is the normal method used in field dormancy studies (Cooke, Eriksson and Junttila 2012). The pattern of bud burst and leaf fall between ash, alder and sycamore is illustrated in Figure 4.2. This shows that alder begins to come into leaf earlier than the other two species and also retains its foliage for longer into autumn and that ash flushes later and loses leaves earlier in autumn than the other two tree species. Basler and Körner (2012) found that there was no effect of photoperiod on bud burst of ash or sycamore, while a study (Vitasse et al 2009) on the effect of temperature on budburst in seven temperate trees showed that of those planted at this trial, ash had the highest sensitivity to temperature, with sycamore being in the middle of the ranking. Spring 2011, when the assessment was made was particularly warm, being the warmest across the UK since 1910 (Met Office undated c). It is likely therefore that the growing season for 2011 was abnormally long for these species.

The phenology data for ash, sycamore and alder were based on monitoring the development and senescence of leaves on the terminal bud but development of leaf area in trees is complex. Focusing on the terminal bud does not allow the pattern of whole tree leaf area to be examined and pioneer trees tend to adopt a different approach to climax species. Climax or forest tree species show a flushing habit of leaf development, whereas pioneers show a successive pattern of leaf development (Kikuzawa 1995). The patterns of flushing between alder, ash and sycamore showed differences (Figure 4.3). The progression of leaf unfolding started earlier in alder but was also more gradual in alder than in the other two species, which exhibited rapid flushing over a relatively short period. The growing season of alder was longer than the other ash and sycamore, which were not significantly different.

The growing season of E. gunnii, being evergreen could not be measured in teh same way as the other species. As an indication, the growing season can be estimated by the period where mean daily temperatures were above 5^{o}C and on this basis it would be the longest for all species, with an index of 1505. The pattern of leaf development in E. gunnii has not been studied, but the growth of the naked buds is triggered by warm temperatures, above 5^{o}C for another cold tolerant species, E. pauciflora (Ball et al 1997). Furthermore this data was readily available, being a climatic variable generated by EMIS (Perks, Harrison and Bathgate 2006).

Stem dry weight, growing season and leaf area

Combining leaf area measurements from 2010 with growing season data from 2011 to create a growth potential index explained 56% of the differences in 2010 stem dry weight of the trees (Figure 4.4).

The nature of the relationship is difficult to identify precisely because of the lack of data at the higher end of the combined leaf area and growing season index. A possible explanation for a curved relationship between growth potential index and stem dry weight is that light interceptance by canopies is not linearly related to leaf area index, but follows a similar curved relationship due to mutual shading of leaves (Cannell, Sheppard and Milne 1988).

Growth is related to three variables: the site resources, the resource capture efficiency and the resource use efficiency (Stape, Blinkley and Ryan 2004). The site resources were the same for all species and the growth potential index provides a measure of the resource capture efficiency of the tree species at this trial. However, the resource use efficiency was not assessed in this trial, but the work of other authors can be used to predict differences between the tree species.

There were differences in growth potential index between species reflecting their resource capture efficiency. A combination of greater leaf area and longer period of growth has enabled alder and probably also E. gunnii to accumulate stem dry weight more rapidly than ash and sycamore (Figure 4.4).

The rate of photosynthesis in a tree species is strongly linked to the nitrogen content of leaves due to large amount of leaf nitrogen devoted to chloroplasts (Poorter and Evans 1998) and alder, being a nitrogen fixing tree is likely to be able to devote larger concentrations of nitrogen to its leaves than the other species. This study also showed that alder exhibited a high SLA, (Figure 4.2) allocating relatively little biomass for every square metre of leaf area. Trees with high SLA are known to exhibit high photosynthetic nitrogen use efficiency (Poorter and Evans 1998) and in general high relative growth rates (Antinez et al 2001). The higher leaf nitrogen concentration and this higher photosynthetic nitrogen efficiency may partly explain why alder has been able to build up leaf area rapidly and also use this leaf area efficiently. A further strength of alder is its relatively long growing season compared with sycamore and ash (Figure 4.3). Alder, is also known to have a short leaf longevity (Koike and Sanada 1989, Kikuzawa 1995), enabling it to replace damaged leaves rapidly.

The most rapid growing species, E. gunnii was able to develop the highest leaf area of any of the species over two growing seasons (Table 4.11), a contributory factor being that it is able to retain leaves for more than one growing season. Other factors contributing to the high productivity are the predicted long period of photosynthetic activity and the high photosynthetic efficiency known of eucalypts, particularly under conditions of high stomatal conductance (Whitehead and Beadle 2004).

The leaf area of alder and sycamore were not significantly different (Table 4.11) and they both exhibit high SLA, yet alder has accumulated a greater stem dry weight (Table 4.10), due to a longer period in leaf and potentially due to higher leaf nitrogen content, allowing higher rates of photosynthesis (Koike and Sanada 1989).

Ash was the slowest growing species, and had the lowest leaf area (Table 4.11) and the shortest growing period of the four tree species (Figure 4.3). A study by Koike and Sanada (1989) found that ash (Fraxinus mandshurica) has a relatively low rate of photosynthesis across a range of level of soil nitrogen content, when compared with alder (Alnus hirsuta) and birch (Betula maximowcziana).

General observations on growth rates

After two growing seasons, E. gunnii had amassed three times the volume of ash (Table 4.9). The superior growth rate of eucalypts is confirmed by other studies, although planting of eucalypts in the UK has been on a small scale and yields based on small plots and using volume functions from other countries. However yields of 25 m^3 ha^{-1} $year^{-1}$ are considered possible from E. gunnii and yields of over 30 m^3 ha^{-1} $year^{-1}$ from E. nitens (Purse and Richardson 2011). However, this investigation has clearly highlighted the risks of planting eucalypts in northern England, with complete failure of plantings of E. nitens over two successive winters and considerable mortality of E. gunnii, over the same periods. However, these were two of the coldest winters in thirty years (Met Office 2010, Met Office 2011). A further constraint to using eucalypts as source of biomass is the high chlorine content, which promotes corrosion in biomass plants, although this can be reduced substantially through torrefaction, to concentrations comparable of wood from trees of other common genera (Keipi et al 2014).

Other than the low specific gravity, the strong growth and excellent survival of alder suggests that it could be a productive SRF species on similar sites to this trial. These results appear to contradict those from EMIS, which predicted lower productivity from the alder (YC6) than the ash and sycamore (YC8). This may be because the predictions of EMIS are applicable to much older stands and this study only examined growth over a period of three growing seasons. Short rotation coppice trials established in the 1990s included alder in addition to poplars, willows and eucalypts. However biomass production of red alder at a screening trial at long Ashton was poor (3.38 odt ha^{-1} $year^{-1}$ over a 4 year rotation) in contrast to the rapid growth of Eucalyptus gunnii (between 16.22 and 22.29 odt ha^{-1} year-1 over a 4 year rotation) (Mitchell et al 1993)..

Generally soil moisture is the main limiting factor restricted alder site suitability (Hall 1990), but a number of potential species exist that could be used in SRF. For example, a study on abandoned agricultural land in Estonia, found grey alder (Alnus incana) produced 15.9 tonnes of dry matter ha^{-1} after five years and grew at a current annual increment of 6.4 tonnes dry matter ha^{-1} at that age (Uri, Tullus and Lohmus 2002). Red alder (Alnus rubra) may also be a possible biomass species for the UK, although even northern, Alaskan provenances are prone to damage by spring frosts (Cannell, Murray and Sheppard 1987).

If reduction in greenhouse gas emissions in addition to biomass production is important, then alder has some important drawbacks. A study of greenhouse gas emissions and uptake from vegetation types in Estonia, showed that both grey alder and alder stands emitted N_2O, with grey alder producing significantly less. Furthermore, emissions of CH_4 were also found in grey alder sites, particularly those growing in wetter conditions. In contrast alder stands were found to sequester CH_4 (Mander et al 2008). A study in Sweden showed that a stand of alder on a drained site produced five times the emissions of N_2O than a similar site with downy birch (Betula pubescens) (Arnold et al 2005).

The long growing season, large leaf area and efficient production of leaves of alder explains its fast growth at this trial. While for E. gunnii a combination of predicted longer growing season, high leaf areas, greater allocation to each m^2 of leaf area and probably longer leaf longevity explain rapid growth at this trial. For SRF, where biomass production is the prime objective, selecting species or provenances of trees which have a long growing season and can rapidly accumulate a large leaf area must be a priority.

Suitability for biomass production

The early results from this trial suggest that if biomass production is an over-riding objective, that ash and sycamore are too slow growing to be attractive to land owners unless significant financial support is available. This was recognised in the report on SRF by Hardcastle (2006). He noted that slower growing native or naturalised species are likely to provide greater anciliary benefits to biomass production, but that the slow growth means they would require additional financial support to make them attractive. Sycamore has exhibited slow growth elsewhere; a trial in Flanders, Belgium, testing birch, poplars, willows and sycamore found sycamore to be slowest growing, producing 1.2 dry tonnes ha^{-1} $year^{-1}$ at a spacing of 6,667 stems ha^{-1} and after four years of growth in the field (Walle et al 2007). This compared with 2.6 dry tonnes ha^{-1} $year^{-1}$ from birch at the same spacing and age and 3.4 and 3.5 dry tonnes ha year from willow and poplar of the same age, but planted at 20,000 stem ha^{-1}. One year growth and survival of birch at Newton Rigg looks promising (Table 4.7), and birch may be a species particularly suited to low intensity silvicultural approaches, focusing on natural regeneration to produce woody biomass.

In terms of risk it is clearly greater when planting E. nitens than E. gunnii for two main reasons. The first area of risk is the poorer tolerance of cold of E. nitens. A report published in 2011 on the DECC SRF trials in England, reported that E. nitens had not survived the winters of 2009-2010 and 2010-2011 at any site, whereas there had been survival of E. gunnii in all the trials in England except the most northerly one, at Roan Farm, Cumbria about 40 km from the trial at Newton Rigg. In the

Scottish trials all the E. nitens was killed in the two cold winters and only one individual E. gunnii remained alive at a trial at South Balnoon, Aberdeenshire (Harrison 2011). The second attribute that makes E. nitens a higher risk for planting is its poor ability to coppice (Boyer undated)   If E. nitens is badly damaged by cold, it is likely to be necessary to replant. Risk of cold damage to eucalypts in the UK could be reduced by planting the best adapted provenances, such as E. gunnii from Lake McKenzie, Tasmania (Evans 1986, Cope, Leslie and Weatherall 2008,) and further lessened by propagating planting material from individuals of particular cold-hardiness. Vegetative propagation of individuals with good growth, straight stems and which are particularly frost-hardy is an approach taken in plantations in the mid Pyrennes of France (da Silva Perez 2011).

Conclusion

It is clear that there are significant differences in growth and survival between the tree species tested at this trial. Results after one growing season (Figure 4.1), show that the alder had the most rapid relative height growth, followed by the eucalypts. However, observations showed that the eucalypts had greater volume growth. By the end of the second growing season all E. nitens had been killed by the cold winter of 2009-2010. Of the surviving three species, the species with greatest stem volume was E. gunnii followed by alder (Table 4.9).   After three growing seasons none of the original eucalypts survived and alder exhibited the highest RHG (Table 4.8), although the specific gravity of the wood was less than the other species (Table 4.10). The LA of the trees after two growing seasons showed E. gunnii to have a particularly high LA whilst LA of alder and sycamore were not significantly different, yet alder had grown much more quickly (Table 4.11). The longer growing season of alder (Figure 4.3) may contribute to this higher growth rate. LAR (stem weight) was particularly low for ash (Figure 4.2), indicating that ash allocates less relative resources to leaves rather than stem. SLA was also low for ash, as well as E. gunnii indicating that these species invest relatively high resources in each m^2 of leaf area, relative to alder and sycamore (Figure 4.2). The strong influence of LA and growing season on productivity was shown by creating a growth potential index by multiplying growing season by LA, as this explained 56% of the variation in stem dry weight between trees (Figure 4.4). The results show that for short rotation forestry on similar sites, alder would be a good candidate, being capable of rapidly accumulating LA and also exhibiting a relatively long growing season, resulting in high productivity. However , studies have shown that stands of alder emit N_20, a greenhouse gas, reducing its suitability for sequestration (Arnold et al 2005, Mander et al 2008)

Acknowledgements

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4.2 Frost damage to eucalypts in a short-rotation forestry trial in Cumbria, England

The following section of the thesis was published in iForest as a peer reviewed publication, the full citation being:

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The article is my work, enhanced by input from my supervisors, Dr Maurizio Mencuccini and Dr Mike Perks.

Introduction

Short rotation forestry (SRF) involves growing trees in plantation at a spacing that allows rapid site capture and which are then harvested at a dbh of between 10 and 20 cm (Hardcastle 2006). The wood produced is normally used to substitute fossil fuels as a source of energy. A number of hardwoods were identified as having potential for SRF in the UK (Hardcastle 2006), but the Read Report (Read et al 2009) highlighted the potential of eucalypts in sequestration of atmospheric carbon, due to their rapid growth. Of these, two species were identified as having particular potential for the UK; Eucalyptus gunnii and Eucalyptus nitens (Hardcastle 2006). There are limited data on growth, but increments of between 3 m^3 ha^{-1} y^{-1} (Kerr and Evans 2011) and 18 m^3 ha^{-1} y^{-1} (Cope, Leslie and Weatherall 2008) have been reported for E. gunnii at a 7 and 25 year rotation respectively and above 30 m^3 ha^{-1} y-^{1} on a 8 year rotation for E. nitens (Purse and Richardson 2001).

It is cold that presents the greatest limitation to growing eucalypts in the UK (Leslie, Mencuccini and Perks 2011). Low temperatures have two main negative impacts on the photosynthesis of eucalypts. The first is damage to tissues due to rupture of cells, while the second is photoinhibition of photosynthesis (Davidson, Battaglia and Beadle 1995). Photoinhibition involves a decrease in the efficiency of photosystem II through the combination of cold temperatures and high levels of sunlight (Close and Beadle 2003). Photoinhibition occurs least and recovery is most rapid in the most cold-tolerant eucalypts (Hovenden and Warren 1998).

Furthermore, low soil temperatures are known to decrease absorption of water by roots (Teskey et al 1984 in Cochrane and Slayter 1988). When the soil is frozen uptake can be seriously disrupted; generally, soil temperatures of -1^{o}C or less will prevent water uptake and can increase dehydration

(Larcher 1957 in Boyce and Lucero 1994). During periods of warm air temperatures with frozen ground, trees must rely on moisture stored in sap reserves and smaller trees will deplete these reserves faster (Boyce and Lucero 1994).

Eucalypts have four main ways of producing leafy shoots; naked buds in leaf axils, accessory buds, dormant (epicormic) buds and buds in lignotubers The latter two; dormant and lignotuber buds are particularly important in producing shoots after significant damage, such as fire or frost. However, it is the naked buds and accessory buds that normally contribute to crown development. The naked buds primarily contribute to the development of leafy shoots, with accessory buds providing an alternative if the naked buds are damaged (Jacobs 1955 in Commonwealth Government of Australia 1999). The naked buds grow when temperatures are above a certain minimum, enabling potentially high productivity, especially when grown as exotics (Beadle et al 1995) as this strategy allows growth through much of the year. Unlike most temperate trees, photoperiod has no effect on growth (Paton 1983). Davidson, Battaglia and Beadle (1995) note that maximum winter growth rates for E. nitens (Deane and Maiden) Maiden in a plantation in Tasmania were only slightly less than maximum rates in summer. However, this lack of dormancy also leaves eucalypts vulnerable to damage through chilling (Davidson, Battaglia and Beadle 1995). The cold winters experienced in the UK, relative to those of Australia means that only a limited range of species, those that are from sub-alpine areas of Australia have survived.

Hardening is a process crucial to providing resistance to cold and also speeds up the recovery time of photsosynthesis, following a period of cold (Davidson, Battaglia and Beadle 1995). In eucalypts a progressive decline in temperature enables hardening within just a few days (Pryor 1976, Paton 1983). Harwood (1980 in King and Ball 1998) describes the importance of hardening, noting that there is little difference in frost resistance between sub-alpine species of eucalypts when they are in an unhardened state, yet when hardened they exhibit considerable variation. In sub-alpine eucalypts hardening is initiated through low temperatures, rather than reduced photoperiod (Eldridge 1969 in Almeira, Chaves and Silva 1994); the crucial temperature for initiating hardening being between 2^{o}C (Paton 1983) and 4^{o}C (Davidson and Reid 1987). However, it is both the level and duration of cold is important to the hardening process and it is a characteristic only of those eucalypts from colder climates (Scarascia-Mugnozza et al 1989).

Hardening does not seem to increase markedly the ability of cold-tolerant eucalypts to limit damage through tolerating supercooling of their tissues, rather it seems to confer resistance to cold through other means (Scarascia-Mugnozza et al 1989). The mechanism involves an increase in concentration of soluble sugars, stabilising cell membranes and possibly also providing photosynthetic precursors enabling more efficient winter photosynthesis (Almeira, Chaves and Silva 1994). Another chemical associated with cold hardiness is anthocyanin, a pigment which is thought to act through reducing absorption of light during photoinhibition and also possibly through a role of quenching antioxidants (Close, Beadle and Battaglia 2004). In frost resistant eucalypts, damage occurs at temperatures well below that which ice forms in the tissues, and so death of cells appears to be related to dehydration (Olien 1978 in Valentini et al 1990, Steponkus 1984 in Valentini et al 1990). As the water potential of ice is lower than liquid water, freezing draws water from the cells and causes them to dehydrate. If this loss of water is sufficient it can cause disruption to cell membranes resulting in leakage (Pearce 2001). This injury, caused by frost dehydration occurs in hardened individuals at a lower temperature than unhardened ones (Valentini et al 1990) and so unseasonal cold is particularly damaging. In a comparison of eucalypt species, the cold-resistant E. gunnii was found to respond rapidly to lower temperatures enabling it to cope with the development of extracellular ice and the associated dehydration of tissues. Scarascia-Mugnozza et al (1989) and Valentini et al (1990) also noted that the capacity of cold tolerant eucalypts to retain intracellular water was considerably increased by cold hardening.

Recent work undertaken in Ireland has focused on two important aspects of cold tolerance in eight species of eucalypt; lethal temperature and the pattern of hardening by Black (unpublished data). Investigation of LT50 (lethal temperature for 50% of the shoots) showed considerable variation between species. Results also showed that the ranking of species in terms of those most cold tolerant differed between winter 2010-2011 and winter 2011-2012. These differences were probably due to different patterns of hardening in the two winters; the earlier winter being colder than the later one. Further investigation showed that the rate of hardening varied between eucalypt species. Black (unpublished data) suggests that when selecting species, LT50 and the rate of hardening should be combined to create a measure of cold tolerance.

A polar air mass moving from continental Europe brought bitterly cold conditions to Great Britain during December 2009 and January 2010, resulting in the coldest winter in England for over thirty years (Met Office 2010), specifically since 1978/ 1979 (Met Office no date a). Across the UK, the mean temperature was 2^{o}C below the 1971-2000 average, with the most severe cold being in the north of the country. For northern Scotland it was the coldest winter on record and for England the ninth coldest since 1910. For northern England the lowest recorded temperature was -17.6^{o}C on 7 January 2010 at Woodford, near Manchester. This was the lowest temperature for that location on record (Prior and Kendon 2011).

The objectives of this study were to examine whether there were significant differences in frost damage and survival between E. gunnii and E. nitens and between larger and smaller trees over the extreme winter period of 2009/2010.

Methods

The methods section is divided in three parts, the first describing the characteristics of the trial, the second the approach used to collect data and the third the methods used to analyse frost damage and survival.

Description of the trial

The trial has been described in section 4.1.

Methods for data collection

The trial at Newton Rigg followed a randomised complete block design with six replicates and plots containing 80 trees each. For this survey a sub-plot of 24 trees was created in each of these plots. All 24 trees within this sub-plot were scored on an eleven point system for frost damage on the 31 January 2010 and then again on on the 1 May 2010. The system for scoring frost damage was based on one used by Evans (1986) except that three parts of the trees were scored separately; the lower stem (within the tree shelters), the upper stem (outside the tree shelters) and the foliage, whereas Evans (1986) scored crown foliage only. The scoring ranges from 0, which is no visible damage, to 10 which represents 91- 100% damage. As a measure of necrosis, the extent to which the cambium had been blackened and the extent of discolouration of the foliage (from healthy green to damaged khaki) was used.

The trial was originally established to test yield of potential SRF species and so maintaining the plots at full stocking was important. In April 2010 the trial was beaten-up and as it was not clear whether the trees would recover, the decision was made to beat up half of the trees in the plots. As such the size of the initial frost damage plots was reduced from 24 trees to 12 trees as the other half of the plot had been replaced with new trees. For E. nitens it was clear the trees would not recover and so all trees were replaced. For E. gunnii, 37% of the original trees were alive and these were not replaced.

The climatic records for the winter of 2009/2010 were obtained from the weather station 1 km away at the Newton Rigg Campus of the University of Cumbria. Figure 4.5 shows the daily minimum and maximum air temperatures over the period between November 2009 and March 2010 at Newton Rigg Campus. In addition to the extreme cold, the daily range in temperature was considerable, reaching 20^{o}C during one twenty four hour period, varying from -14^{o}C to 6^{o}C. Twenty four hour temperature fluctuations of nearly 10^{o}C were frequent during the winter, due to the combination of cold nights and clear sunny days. During December, January, February and March, the grass minimum temperature fell below freezing on twenty four, twenty eight, twenty five, twenty one and fourteen days respectively. On the 9 January 2010 the grass minimum dropped to a low of -17°C. The period of sunshine was generally above the 1971-2000 average (Met Office no date d). During the period between mid December and mid January there was almost constant snow cover, with depths of up to 19 cm. During the remainder of the winter there were only infrequent, small falls of snow, the ground being bare for much of the time.

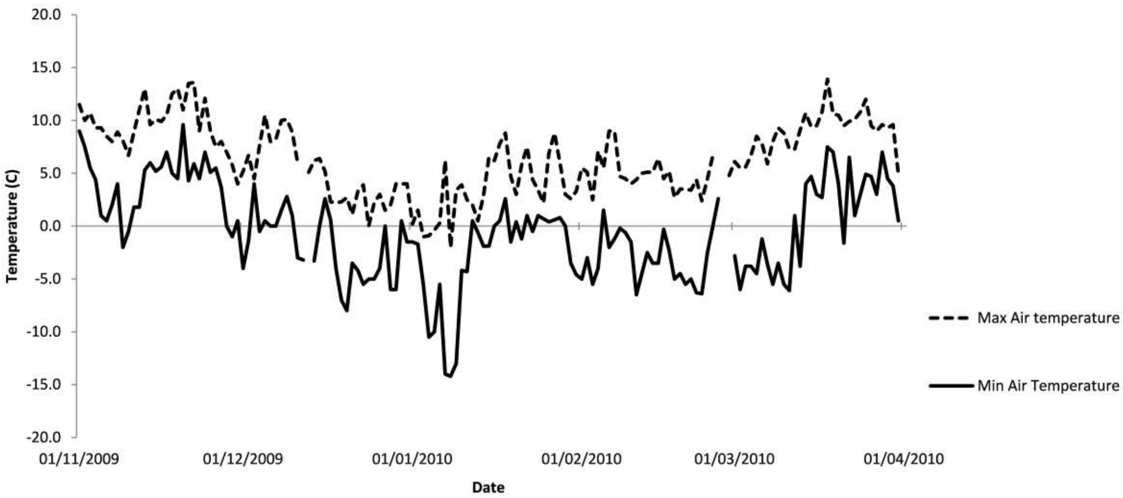

Figure 4.5: Maximum and minimum air temperatures over the winter of 2009/ 2010 using data from the Newton Rigg weather station.

Analysis of data

Differences in the distribution of frost damage score data for cold damage at lower stem, upper stem and foliage between E. gunnii and E. nitens were tested for normality using a Shapiro Wilkes test and were found to be very highly significantly ($p<0.0001$) different from normal (Appendix 7.25 presents the statistical output), so a non parametric Kolmogorov-Smirnoff test was used to test for differences in the frost damage scores between the two species.

The role of tree size on cold damage was investigated by dividing the trees into quartiles by their height in January 2010. For these quartiles, the data on cold damage was tested for conformance to a normal distribution using a Shapiro Wilkes test. By quartile and by block scores for cold damage and for E. gunnii and for E. nitens were found to be significantly different from normal and non-parametric Kruskal Wallis tests and Mann Whitney tests were applied to the data to test significance of differences (details of statistical analyses are presented in Appendix 7.26 and 7.27). For survival in May, after full winter, a Chi squared test was used to determine whether significant differences exist in survival between between the quartiles for E. gunnii (Appendix 7.28 for statistical analysis) but not E. nitens as too few survived to enable a meaningful analysis.

The influence of location within the trial on frost damage was investigated by analysing differences in damage and survival between blocks. The data were tested for normality using a Shapiro Wilikes test and significant differences were detected. Kruskal Wallis tests and Mann Whitney tests were applied to determine if differences were significant (Appendix 7.29 and 7.30). Differences in survival between blocks of E. gunnii in May were also examined using a Chi squred test (Appendix 7.31).

Results

The pattern of frost damage noted on 31 January 2010 in the lower stem, upper stem and the foliage was compared between E. gunnii and E. nitens using a Kolmogorov- Smirnoff test and was found to be very highly significantly different (P<0.0001) (Statistical analysis is presented in Appendix 7.25). E. nitens was found to be more susceptible to damage by frost to stem and foliage, this being manifested in higher scores for frost damage. Despite very low temperatures in January of -14^{o}C minimum air temperature or -17^{o}C grass minimum, the E. gunnii showed relatively little visible damage (Figure 4.6), whereas the damage to E. nitens was very obvious, particularly to its foliage (Figure 4.7). In January, survival remained high with that of E. gunnii being 93% and of E. nitens being 93%. The results of the assessment of 1 May 2010 showed that there had been a substantial increase in damage, particularly to foliage of both species and considerable further mortality. Survival of E. gunnii had declined to 35% whereas for E. nitens it had dropped to less than 1%.

There appeared to be a relationship between tree height and damage. The median heights for each quartile are shown in Table 4.13 with the overall ranking of damage by quartile. In E. gunnii damage to lower stem, upper stem and foliage was greatest in the quartiles containing the smaller trees. A Kruskal Wallis test was used to examine differences in damage between quartiles (Appendix 7.26 for details). There were significant differences between quartiles for damage in the lower stem (p=0.023) and foliage (p=0.030), but not the upper stem (p=0.052). Mann Whitney tests were used to identify where these differences originated. The results from these are described in Table 4.14 and the damage to the lower stem and foliage for the quartile with the smallest trees was significantly different from the large quartile and for the foliage for the largest quartile. Lower stem damage was also significantly different in small trees than large trees (Table 4.14).

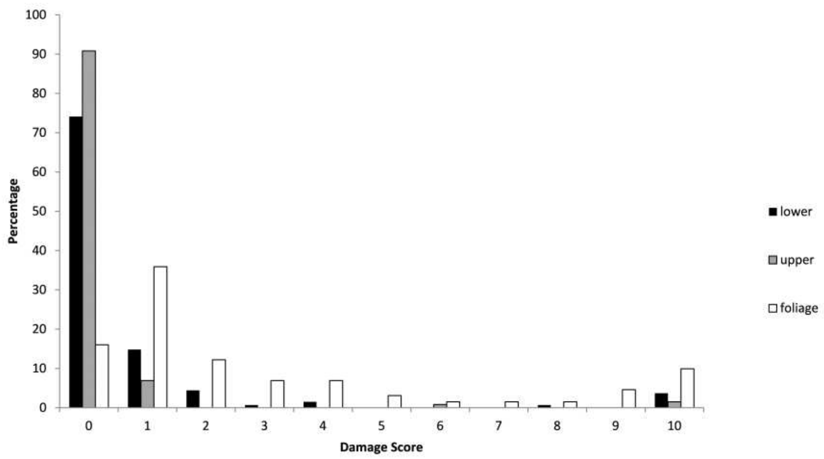

Figure 4.6: Frost damage in upper stem, lower stem and foliage of *E. gunnii.* 0=no damage, 1 = 1-10% damage, 2=11-20% damage, 3 = 21-30 damage, 4 = 31-40% damage, 5=41-50% damage, 6=51-60% damage, 7=61-70% damage, 8-71-80% damage, 9=81-90% damage, 10=91-100% damage.

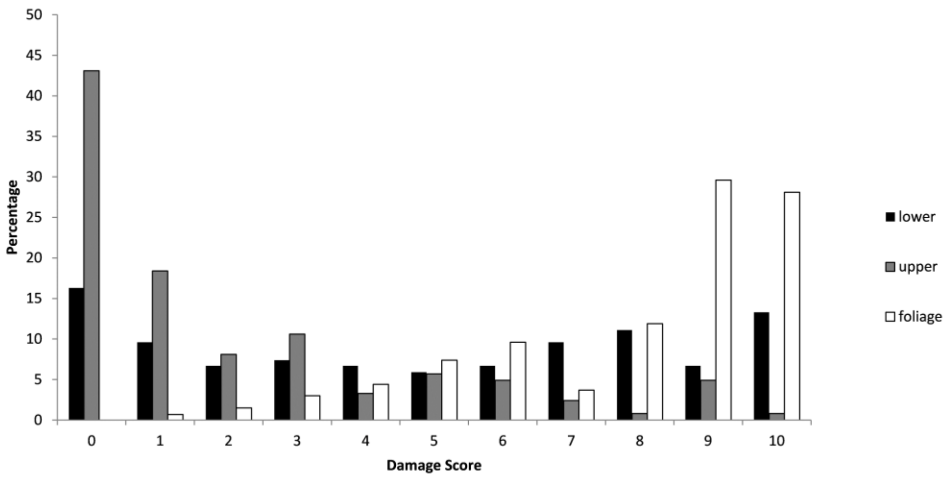

Figure 4.7: Frost damage in upper stem, lower stem and foliage of *E. nitens*. 0=no damage, 1 = 1-10% damage, 2=11-20% damage, 3 = 21-30 damage, 4 = 31-40% damage, 5=41-50% damage, 6=51-60% damage, 7=61-70% damage, 8-71-80% damage, 9=81-90% damage, 10=91-100% damage.

For E. gunnii an examination was undertaken to determine whether survival in May 2010 after months of freezing conditions was related to tree height. While survival was lowest (30%) in the quartile containing the largest trees it was next lowest in the smallest trees (32%) and highest survival was in the trees in the second smallest quartile (41%). A Chi squared test indicated that differences between survival in the quartiles were not significant (p=0.348). Details of the statistical analysis are shown in Appendix 7.28.

	E. gunnii				*E. nitens*			
Height of trees by Quartile	Median height (cm)	Damage Score			Median height (cm)	Damage score		
		Lower stem	Upper stem	Foliage		Lower stem	Upper stem	Foliage
Smallest	98	3	4	4	73	4	4	4
Small	131	4	3	3	108	2	2	2
Large	155	1	2	2	122	3	1	3
Largest	175	2	1	1	147	1	3	1

Table 4.13: Ranking of damage score in January 2010 by tree height, divided into quartiles, where 1 = lowest damage to 4 = highest damage.

		Quartile		
		Small	Large	Largest
Quartile	Smallest	SL 0.960 FO 0.114	SL **0.012** FO **0.019**	SL 0.313 FO **0.002**
	Small		SL **0.003** FO 0.367	SL 0.153 FO 0.194
	Large			SL 0.075 FO 0.735

Table 4.14: Probabilities from Mann Whitney U tests comparing damage in *E. gunnii* between quartiles of tree height (SL=stem low, SH=stem high and FO=Foliage).

As with E. gunnii, the E. nitens trees were divided into quartiles by height in January 2010 and as the data was not normally distributed a Kruskall Wallis test was used to identify if the differences in frost damage by quartile were significant (For statistical analysis, see Appendix 7.27). Differences between quartiles in terms of foliage and lower stem damage were very highly significant ($p<0.0001$). Mann Whitney tests were applied to the foliage and lower stem data by quartile to identify where these differences lay and only the smallest quartile showed damage significantly different to others (Table 4.15).

A Kruskal Wallis test showed that differences in damage in January between blocks for E. gunnii were not significant for lower stem and foliage but were highly significant for upper stem (statistical analysis is presented in Appendix 7.29). The level of upper stem damage was however low in all blocks. A similar analysis of damage in E. nitens in January and E. gunnii in May showed no significant differences in damage in lower stem, upper stem and foliage by block (statistical analyses are presented in Appendix 7.30 and 7.31 respectively). There were insufficient E. nitens surviving in May to conduct an analysis of damage by block.

		Quartile		
		Small	Large	Largest
Quartile	Smallest	SL: **0.0001** SH: **0.0001** FO: **0.0001**	SL: **0.001** SH: **0.0001** FO: **0.0001**	SL: **0.0001** SH=**0.001** FO: **0.0001**
	Small		SL: 0.878 SH: 0.375 FO: 0.586	SL: 0.152 SH: 0.398 FO: 0.395
	Large			SL: 0.241 SH: 0.982 FO: 0.169

Table 4.15: Probabilities from Mann Whitney U tests comparing lower stem damage and foliage damage in *E. nitens* between quartiles of tree height.

Survival of E. gunnii by block by May varied from 54% to 20% and a Chi squared test showed the differences not to be significant (p=0.195: statistical analysis is presented in Appendix 7.31). Despite evidence of epicormic growth in trees that were left when part of the plots were replanted none of those that were recorded as being dead recovered during the summer. There were insufficient trees surviving of E. nitens in May to undertake a similar analysis of survival between January and May by quartile or by block.

Discussion

The influences determining the degree of damage to eucalypts from cold are complex and are related to a number of factors which are summarised in Figure 4.8. However well adapted temperate eucalypts are to the UK climate, the winter of 2009/ 2010 was the coldest in over thirty years (Met Office 2010) and the combination of severe cold and almost three months of days where temperatures dropped below freezing will have caused severe plant stress. Further, due to clear skies, the range in temperature over twenty four periods was considerable, resulting in variation in temperature of 20^{o}C during one twenty four hour period in January, during which the trees would have experienced periods of freezing and thawing of above ground and below ground tissues. Two factors may have reduced damage somewhat; the gradual but steady decline in temperatures during December (Figure 4.5) would have allowed the trees to harden and also damage may have been mitigated to a degree by the insulating layer of snow that lay on the ground from mid December to mid January, protecting the roots from the extreme air temperatures.

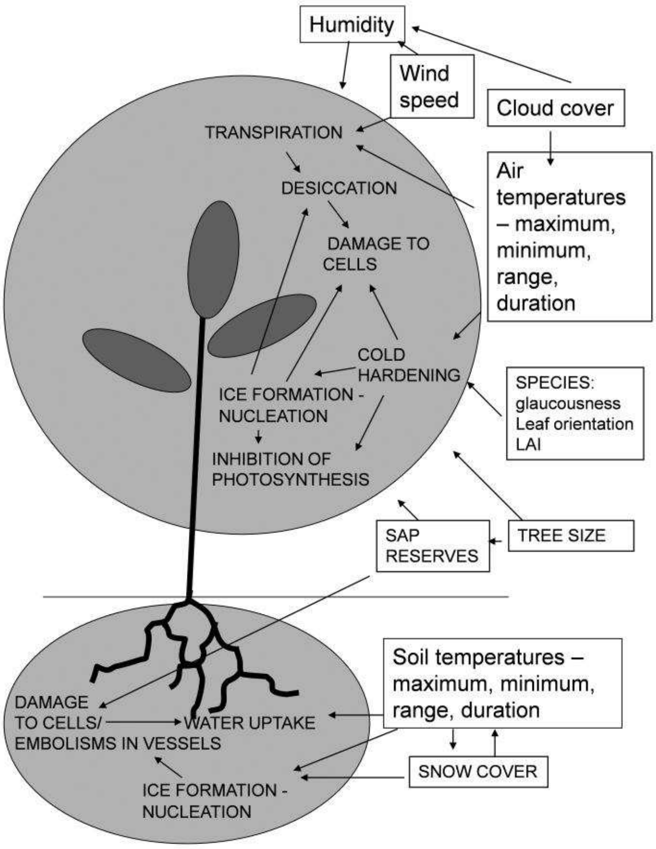

Figure 4.8: Summary of external and internal physiological factors affecting frost damage.

The two species of eucalypt tested in the trial have different climatic tolerances, including their capacity to resist cold (Booth and Pryor 1991). It is E. gunnii that inhabits a colder alpine environment in Tasmania, compared with the montane, lower latitude areas occupied by E. nitens on the main portion of Australia. E. gunnii is noted as being one of the most cold hardy species, being highly resistant even in an unhardened state (Davidson and Reid 1987). This is supported by results from this trial; by the end of January, E. nitens had suffered significantly worse damage then E. gunnii from the cold (Figure 4.6 and Figure 4.7). However, in early February many of the terminal buds of E. nitens still appeared green, flexible and undamaged (Hepburne-Scott pers. comm.). By May the injury to the trees had increased markedly and only 35% of the E. gunnii remained alive, while less than 2% of the E. nitens had survived.

Work by Black (unpublished data) in Ireland has shown that there are considerable differences between cold-tolerant eucalypts not only in terms of lethal minimum temperatures but also in their pattern of acclimation to cold. Absolute lethal temperature and ranking by seasonal variance in lethal temperature were combined to produce an overall rank of cold tolerance. Of seven species of eucalypts, E. nitens was found to be the poorest in terms of cold tolerance, with E. gunnii being fourth out of the seven species. This contradicts other work that suggests E. gunnii is particularly cold-tolerant (Davidson and Reid 1987).

The evaluation of cold damage to the trees was undertaken using a visual scoring system, but a more reliable and quantifiable approach for evaluating damage to the foliage would have been to measure chlorophyll fluorescence as detailed in Perks et al (2004). Also, the impacts of cold damage are more often measured under controlled conditions, for example using a freezing cabinet. This is because of the many factors that influence cold damage in the field, such as variation in; micro-topography and sky exposure, in the frost hardiness of the trees across and between seasons and between and within populations. The assessment showed clearly that woody tissues suffered less extensively from damage from the cold than the foliage in both species of eucalypt, an observation supported by others (Scarascia-Mugnozza et al 1989).

In the January 2010 assessment of damage there was considerable variation in frost injury between trees, even those adjacent to one another. While some individuals exhibited almost complete damage to foliage, others remained almost uninjured. This variation could be due to differences in; the genetic composition of individuals, the size of the individuals, the micro site they occupied or their treatment during planting and tending. Considerable variation in the frost resistance of provenances and individuals within provenances has been noted in both E. gunnii (Potts 1985, Potts and Reid 1985a, Potts and Reid 1985b) and E. nitens (Tibbits and Reid 1987, Tibbits and Hodge 2003, Hamilton and Potts 2008) in their natural habitats. A study of frost tolerance of 101 origins of E. nitens planted in Tasmania, showed the western provenances of the central highlands of Victoria and those from New South Wales to be superior (Tibbits and Reid 1987), while from early results, Evans (1986) found origins of E. nitens from Victoria were most cold hardy in trials in Great Britain. For E. gunnii there is convincing evidence from British trials (Evans 1986, Cope, Leslie and Weatherall 2008) that provenances from Lake MacKenzie are more frost tolerant.

The finding that larger trees are more resistant to damage, highlights the importance of obtaining rapid early growth so as to obtain a tree of 1-1.5 m height before the onset of winter. Rapid growth is important, as larger trees have greater sap reserves and once trees reach 2-6m the sensitive growing tips are usually above mild growing season radiation frosts (Davidson and Reid 1987). Furthermore, larger trees exhibit greater physiological maturity and tolerance to environmental stresses than smaller trees of the same age. Ensuring rapid establishment is therefore crucial, including effective weed control and ensuring the trees receive adequate nutrition. Furthermore, good nutrition has also been shown to be important through reducing the extent of photoinhibition in seedlings of E. nitens during cold periods (Close and Beadle 2003). The increase in damage to the very largest trees at the trial may be explained by an imbalance between the root: shoot ratio; many had proven to be unstable being prone to lean and had required additional staking

The effects of frost can be difficult to predict as both fast recovery and long-term deleterious effects have been noted (Ball 1994 in King and Ball 1998). The effects of repeated frosts can have a compounding effect on growth and survival, especially in trees is a phase of rapid, early growth where death of mature leaves and developing shoots can delay investment of resources into new leaves (Ball et al 1997 in King and Ball 1998). The weak growth in the summer of 2010 and complete mortality of the E. gunnii that survived the winter of 2009-2010 in the subsequent, milder winter supports this observation. The results from this trial show that following severe cold damage it is best to replant young eucalypts as recovery is unlikely and even those individuals that have survived are likely to have lower growth and survival.

Conclusions

The results of this study support the results of others from both field trials (Evans 1986) and laboratory tests (Booth and Pryor 1991) that E. gunnii is more cold tolerant than E. nitens. Only two of the 144 trees assessed of E. nitens survived by May 2010, compared with 43 of the 144 trees of E. gunnii. Despite the once in thirty year conditions experienced in winter 2009-2010 and the trees being less than one year on the site, the better survival of E. gunnii suggest in terms of adaptability that it is a species that could be used for producing woody biomass even in northern parts of Britain. Also, it is probable that survival of E. gunnii at the site would have been enhanced by use of material with the origin of Lake Mackenzie, that best adapted to British conditions (Evans 1986, Cope, Leslie and Weatherall 2008). Relative damage, but not survival is related to the size of the young trees, with larger trees being more resistant. It is therefore imperative that transplants, through intensive silviculture, provision of adequate nutrition, and are given the greatest opportunity to establish effectively and grow rapidly before their first winter, when they are particularly vulnerable.

Acknowledgements

The authors would like to thank the following people; Alastair Chalmers of Pyroclassic Fires for funding half the establishment costs of the trial, Pat Tyers and Graham and Chris Leslie for helping with data collection and also Kevin Black for providing a draft manuscript of his report on cold tolerance studies on eucalypts in Ireland. They also thank Dr Conor O'Reilly and Dr Euan Mason for highlighting areas requiring improvement in the original manuscript.

Chapter 5 Characterising volume and growth of *Eucalyptus gunnii*

Introduction

Of the eucalypts, cider gum (Eucalyptus gunnii), a high altitude species, endemic to Tasmania is one of the hardiest species (Sheppard and Cannell, 1987; Booth and Pryor 1991). It has a long history in the United Kingdom, was the first Australian tree to be successfully grown outdoors and is now relatively common in gardens and parks (Purse 2010). There are specimens of individuals planted almost 100 years ago, a testament to the good adaptation of the species to parts of the UK where cold is not a limitation (Purse 2010a). Results from provenance trials in the UK have indicated the superiority in growth and survival of the Lake McKenzie provenances (Evans 1986, Cope, Leslie and Weatherall 2008) and there is potential for enhancing cold hardiness in E. gunnii through selection; Evans (1986) described some individuals that had survived minimum temperatures of -18 ^{o}C.

The potential for improving yields of E. gunnii through tree improvement and rigorous silviculture can be evidenced from trials in France, where a long term pulp plantation programme has developed clones of E. gunnii, selected for productivity and cold tolerance. Furthermore, E. x gundal, a hybrid between E. gunnii and E. dalrympleana has been created, which combines the better growth rates and form of Eucalyptus dalrympleana with the greater cold tolerance of E. gunnii. Establishment and tending practices are intensive and growth from these plantations has been impressive; standing volumes of between 160 and 215 m^3 ha^{-1} or mean annual increments of between 13 and 18 m^3 ha^{-1} $year^{-1}$ have been achieved over a 12 year rotation (AFOCEL 2007).

Growth of E. gunnii in the UK has been estimated in a small number of studies (Kerr and Evans 2011, Cope, Leslie and Weatherall, 2008), but a complicating factor is the lack of functions to relate dbh and height to volume for trees grown in the UK. Volume functions for Eucalyptus gunnii are available for trees grown in France in the mid Pyrenees (AFOCEL 2003a) and these have been used to estimate tree volumes in the UK (Kerr and Evans 2011, Cope, Leslie and Weatherall, 2008). A general volume function for cold tolerant eucalypts developed in Chile (Purse and Richardson 2001) has also been used to calculate volumes (Cope, Leslie and Weatherall 2008). Other approaches taken to calculating tree volumes of E. gunnii in the UK include the use of the tariff system, as described in Matthews and Mackie (2006), which is commonly used for estimating standing timber volumes in the UK. This was applied to E. gunnii diameter and height data with certain assumptions on stem form (Kerr and Evans 2011). It is likely that the French volume function, given it is based on measurements of E. gunnii, estimates volumes of trees grown in the UK with reasonable precision and this assumption is tested in this study.

There are no continuous measurements of volume growth but there are assessments of standing volumes of E. gunnii in the UK, from which a mean annual increment can be calculated. Table 5.1 describes some of the published estimates of growth reported in the literature and from personal communications. All the estimates of volume were based on measurements of dbh and height, from which volume is estimated making certain assumptions on stem form. The annual increments in weight for the New Forest study were calculated from volumes and an assumed wood density, but for Daneshill the values were based on the actual weight harvested. Table 5.2 presents results of growth from trials growing E. gunnii as short rotation coppice.

Table 5.1. Published and other information on growth rates of non-coppiced *E. gunnii* in the UK. [1] Wooddisse pers comm. (2012), [2]Kerr and Evans (2011), [3]Bennett and Leslie (2003), [4]Cope, Leslie and Weatherall (2008), [5]Leslie, Mencuccini and Perks (2013). [a]Mean of three provenances, [b] Mean of five Lake McKenzie seed lots. [c]Mean of two provenances.

Location	**Age (years)**	**Standing volume or biomass**	**Mean annual increment**	**Notes**
Daneshill[1]	5	85 t ha^{-1}	17 t ha^{-1} $year^{-1}$	From a mix of stands of *E. gunnii* and the more productive *E. nitens*. Dead stems were standing for six months so wood was relatively dry. Stocking approximately 2,940 stems ha^{-1}
New Forest[2]	7	97 m^3 ha^{-1}	13.9 m^3 ha^{-1} $year^{-1}$ / 6.2 t ha^{-1} $year^{-1}$	From a spacing experiment, planted at 5,102 stems ha^{-1}
New Forest[2]	7	19 m^3 ha^{-1}	2.7 m^3 ha^{-1} $year^{-1}$	From a spacing experiment, planted at 1,276 stems ha^{-1}
Thetford[3a]	21	261 m^3 ha^{-1}	12.4 m^3 ha^{-1} $year^{-1}$	From small, line plots in a provenance trial, planted at 1,850 stems ha^{-1} with 48% survival giving 888 stems ha^{-1}.
Glenbranter[4b]	25	452 m^3 ha^{-1}	18.1 m^3 ha^{-1} $year^{-1}$	From small, line plots in a provenance trial, planted at 1,842 stems ha^{-1} with 96% survival giving 1,768 stems ha^{-1}
Chiddingfold[5c]	25	435 m^3 ha^{-1}	17.4 m^3 ha^{-1} $year^{-1}$	From two 0.01 ha plots measured in a small block planting, mean stocking of 1,150 stems ha^{-1}.

Table 5.2. Published and other information on growth rates in oven dry tons (odt) per hectare per year of short rotation coppice *E. gunnii* in the UK and Ireland. [1] Forrest and Moore (2008), [2]Mitchell, Ford-Robertson and Watters (1993), [3]Potter (1990). [a]But stools are 13 years old and been successively harvested every year.[b]Age of shoots after being cut back to initiate coppice at one year old. [c] mean of yields in 1985/86 and 1986/87.

Location	**Age (years)**	**Mean annual increment (odt ha^{-1} year^{-1})**	**Notes**
University College Dublin[1]	1[a]	12.6	Planted at 2,657 stems ha^{-1}
University College Dublin[1]	1[a]	15.4	Planted at 3,267 stems ha^{-1}
Long Ashton[3]	2[b]	13.0	Planted at 10,000 stems ha^{-1}
Long Ashton[3]	2[b]	9.9	Planted at 2,500 stems ha^{-1}
Mepal[3]	2[b]	12.7	Planted at 10,000 stems ha^{-1}
Mepal[3]	2[b]	4.2	Planted at 2,500 stems ha^{-1}
Whitney[3]	2[b]	4.7	Planted at 10,000 stems ha^{-1}
Whitney[3]	2[b]	2.5	Planted at 2,500 stems ha^{-1}
Long Ashton[2]	4[b]	18.4[b]	Planted at 10,000 stems ha^{-1} but 60% survival, so 6,000 stems ha^{-1}
Long Ashton[3]	4[b]	13.5	Planted at 10,000 stems ha^{-1}
Long Ashton[3]	4[b]	8.3	Planted at 2,500 stems ha^{-1}

To understand the pattern of growth over time and conduct economic analyses, growth curves are required. For E. gunnii, the only growth curves published are from plantations in France (AFOCEL 2003a, FCBA 2012). There are no curves for trees grown in the UK and no continuous time series data sets in the UK covering the predicted rotation lengths for short rotation plantations of E. gunnii. There are however data from measurements of height or diameter or height alone at a point in time or sometimes several measurements over a restricted period of time from trials established by Forest Research from the 1980s and a few other trials. Most of these provide data on growth in the first five years but there are a few measurements of older trees.

This study was devised to provide preliminary estimates of growth of E. gunnii in the UK. Specifically, this study had three aims:

1. To validate the precision of available volume functions, relating height and dbh to stem volume when applied to E. gunnii.
2. To develop a generalised growth curve relating volume per unit area to stand age.
3. To investigate patterns of growth in two sites, one in the south and one in the north of Great Britain.

Methods and analysis

Study 1: Validation of volume functions

During 2011 and 2012 stem volume data were collected of trees of ages ranging from 6 years to 43 years, and from southern, central and northern areas of the UK (Figure 5.1) to test the applicability of the AFOCEL (2003a) and Shell (Purse and Richardson 2001) volume functions to trees in the UK. These data were collected using three techniques; from trees felled for stem analysis, from trees where taper was measured using a Lazer Technology Inc. Criterion RD1000 optical dendrometer and from trees that were scanned using a Leica Terrestrial Laser Scanner (TLS) and their volumes estimated using a programme devised by Dr Eric Cassella at Forest Research. The number of trees, their age, the method used to measure volume and their locations are shown in Table 5.3.

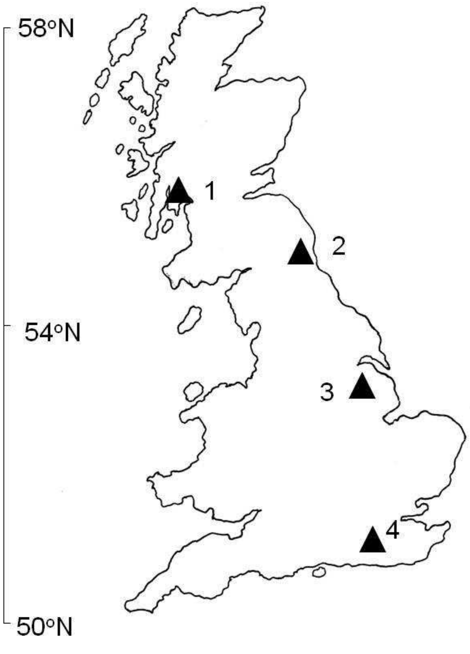

Figure 5.1: Location of sites for tree volume data collection (1=Glenbranter, 2=Woodhorn, 3=Thoresby, 4=Chiddingfold).

For the optical dendrometer, measurements of diameter and height were taken up the stem from the base, the number being dictated by the length that could be easily viewed up the stem and varying from 5 to 8 measurements. A separate study of E. nitens stem form and volume showed that the stem volumes estimated from 5 to 8 optically measured diameters and the full ten diameters from felled trees were not statistically significantly different from each other ($p>0.05$).

Table 5.3: Location, number, age of trees and measurement method for trees used in the stem form study.

Location	Number of trees	Age	Method
Woodhorn	473	6	Terrestrial laser scanner
Thoresby	25	10	Optical dendrometer
Chiddingfold	10	27	Trees felled for stem analysis
Glenbranter	2	43	Trees felled for stem analysis

Stem volumes were calculated by summing the volumes calculated for each section. The volume for each section was estimated using Smalian's formula (Phillip 1994), for all sections except the top of the tree, where the equation for a cone was used (Phillip 1994). The equation for Smalian's formula is shown below, followed by the equation for the volume of a cone:

Smalian's volume = $L(\pi \bullet d_1^2 + \pi d \bullet_2^2)/8$

Volume of a cone = $(\pi \bullet d_2^2 \bullet h)/12$

Where L is length of section, d_1 is the diameter at the top of the stem section and d_2 is the diameter at the bottom of the stem section.

The volumes calculated were compared to the tree overbark volumes estimated using the AFOCEL volume equation (AFOCEL 2003a) and Shell function (Purse and Richardson 2001). The AFOCEL equation incorporated height and diameter at breast height, where V= overbark volume (m^3), dbh = diameter at breast height (cm) and h=height (m).

$$V=(-5.04+(0.03556 \bullet dbh^2 \bullet h))/1000$$

The Shell function was developed for cold tolerant eucalypts in general and is not specific to E. gunnii. This assumes a form factor of 0.35 giving a formula of:

$$V=0.35(\pi \bullet dbh^2 \bullet h))/40000$$

The accuracy of the Shell and AFOCEL functions was compared by calculating a value for the residual (R), the percentage difference between measured stem volume (V_m) and calculated stem volume (V_c) using this equation:

$$R = (100 \bullet (V_m - V_c))/V_m$$

These were plotted against tree stem volume to bias in each the application of each equation. A linear regression of measured stem volume (y axis) against predicted stem volume (y axis) for each equation was performed, as described in Piñeiro et al (2008). To estimate biomass, volume was converted to biomass using a bulk density of 1050 kg m^{-3} and a dry weight density of 500 kg m^{-3} (AFOCEL 2003).

Study 2: Developing a generalised growth function

The lack of continuous growth data and geographical spread of tree growth data for E. gunnii in Britain presents a considerable problem when developing a generalised growth curve. Data on growth were extracted from files of trials established by Forest Research, Nottinghamshire County Council and Thoresby Hall Estate and means for stands at the sites calculated for height and, where available, for dbh. These data are summarised in Table 5.4 and the locations in Figure 5.1. Age in years is presented to two decimal places (one decimal place is not sufficiently precise to differentiate between months; for example both 3 months and 4 months rounded would be 0.3 years)

These data were used to develop a height by age curve, a dbh by height curve and through applying the AFOCEL volume function a volume by age curve. Due to the small amount of data available in general and of time-series data in particular, equations proven to accurately model height by age were used for the historic UK data. The equations used (Zeide 1993, Devaranavadgi et al 2013) are shown below:

1. Gompertz model: $y = a\bullet\exp(-\exp(b^{-cx}))$
2. Exponential model: $y=a\bullet\exp(b(x+c))$
3. Richard's model: $y=a\bullet(1-\exp(b\bullet x)^{c})$
4. Korf model: $Y=a\bullet(\exp(b\bullet x^{-c})$

Where y is height and x is age in years, with a, b and c being parameters in the models.

To enable volume growth to be estimated, a function relating diameter to age was also required. As diameter is strongly influenced by stocking, data on diameter from trees planted at stockings of between 1,200 and 2,500 stems ha^{-1} were used to derive a relationship between height and dbh using regression. To derive this relationship, the curve fitting tool in SPSS v19 was used which enables eleven different types of function to be fitted.

All height data across the range of stockings was used to fit a height: age curve, as height is relatively independent of stocking. This was undertaken using the nonlinear regression tools in SPSS v19.

Table 5.4 Tree size data: location, height, dbh, sample size and stocking.

	Age (months)	Age (yrs)	Height	N	Dbh	Stocking
Alice Holt	5	0.42	0.5	59		1,313
Alice Holt	14	1.17	1.4	58		1,291
Alice Holt	26	2.17	1.2	50		1,113
Alice Holt	38	3.17	2.3	49		1,091
Chiddingfold	29	2.42	1.5	975		1,716
Chiddingfold	85	7.08	5.4	975		1,202
Chiddingfold	311	25.92	22.8	23	19.1	1,150
Chiddingfold	336	28.00	19.4	10	19.2	N/A
Dalton	5	0.42	0.7	N/A		2,500
Dalton	16	1.33	1.3	N/A		2,317
Dalton	35	2.92	2.0	N/A		2,317
Dalton	282	23.50	17.8	N/A	23.3	2,584
Daneshill	28	2.33	5.4	14	8.3	2,940
Daneshill	41	3.42	7.6	14	12.3	2,940
Daneshill	53	4.42	8.1	14	11.4	2,940
Daneshill	65	5.42	10.6	13	12.4	2,940
Glenbranter	29	2.42	1.2	78		1,330
Glenbranter	34	2.83	1.2	78		1,330
Glenbranter	54	4.50	2.5	79		1,347
Glenbranter	107	8.92	9.3	N/A	8.6	N/A
Glenbranter	120	10.00	9.7	79	9.8	1,347
Glenbranter	178	14.83	15.8	5	13.7	N/A
Glenbranter	308	25.67	14.9	74	19.1	1,262
Glenbranter	516	43.00	30.1	45	35.2	N/A
New Forest	5	0.42	0.1	130		1,275
New Forest	45	3.75	7.2	130		1,275
New Forest	53	4.42	7.3	130	5.8	1,275
New Forest	75	6.25	10.5	130	8.0	1,275
Thoresby	126	10.50	16.4	35	20.7	2,500
Tintern	2	0.17	0.4	60		3,265
Tintern	16	1.33	1.2	28		3,265
Tintern	28	2.33	1.4	63		3,265
Tintern	29	2.42	2.0	59		3,265
Tintern	43	3.58	3.5	28		3,265
Tintern	55	4.58	3.5	63		3,265
Wykeham	18	1.50	1.5	N/A		N/A

To obtain a preliminary estimate of volume growth across Britain, the predicted height and predicted dbh at those heights up to an age of twenty years were converted to volumes using the AFOCEL volume function to obtain a stem volume for trees up to twenty years. The analysis was restricted to the first twenty years as self thinning and other mortality is likely to have had an impact on stocking in later years. Also growth is likely to reflect that achievable in well-managed stands as it is probable that inter-tree competition was not excessively intense in the first twenty years. After twenty years of age it is likely that competition at later ages will have reduced growth rates in all but the dominant trees in the stands. A median initial stocking for the plots of 1,350 stems hectare^{-1} was used to convert stem volume to volume per hectare and it was assumed there was no mortality.

Study 3: Growth functions from stem analysis on trees from Chiddingfold and Glenbranter

To provide some continuous growth data for E. gunnii trees, ten trees were felled at Chiddingfold and two at Glenbranter and growth assessed using stem analysis. Table 5.5 describes the two sites. Stem analysis is a well-established technique in tree growth studies and has been used for analysing growth in eucalypts (Kariuki 2002).

For the trees at Chiddingfold, ten discs were cut at the base, dbh and at nine equidistant points up the stem up the stem, while for Glenbranter trees five discs were cut. These were scanned at 1,200 dpi at a 100% scale using an Epson Expression 1,000 A3 flatbed scanner to produce detailed scans of the discs. Regent Instruments Windendro 2004 tree ring analysis software was used to measure annual ring widths across eight radii evenly distributed around the discs. The mean annual ring width across these eight radii was used to calculate volume in a Microsoft Excel spreadsheet. A Prior binocular microscope at 10x magnification was used to help determine the boundaries of some of the narrower rings on the discs. The number of dics and radii sampled should provide a precise estimate of volume growth. Newton (2004) in an assessment of sampling strategies for estimating volume growth, determined that ten to eleven equidistant sections of the stem and four radii based on the smallest and largest diameters provided data that is effective.

Volume growth was estimated by identifying height at each age and cross sectional area at each age. Height attained at each age was estimated at ten (Chiddingfold) or five (Glenbranter) points up the stem using the age minus the number of rings on the disc at that section. Height for the final year's growth in each section was modified by applying Carmean's formula, identified by Dyer and Bailey (1987) as most precisely estimating length of the final year's "hidden tip" in the stem sections. Annual height growth within stem sections was calculated by dividing the length of the sections by the number of years' growth in that section. A curve was fitted to the height data by age using the best fitting (in terms of high R^2 and low standard error of the estimate) one of the four formulae applied to the historic data using SPSS v19.

To determine annual cross sectional area growth, ring widths obtained through Windendro from the scans of the discs were converted to cross sectional areas. Volumes for each year were then calculated by applying Smalian's formula to the cross sectional area attained at the end of that year multiplied by the section length. Where annual growth ended in the stem section the volume was calculated by using the equation for the volume of a cone applied to the cross sectional area and the estimated height at which growth stopped for that year. For each year the volume growth in all sections was added together to obtain growth for that year, the current annual increment (CAI). Mean annual increment (MAI) was also calculated by dividing the total volume for a particular year by the age. The stem analysis provided CAI, MAI and cumulative volume production for each tree.

Table 5.5: Site description (Forestry Commission no date e, Forest Research no date f) and climate variables for Glenbranter and Chiddingfold generated by ESC (Pyatt, Ray and Fletcher 2001). AT5 = accumulated temperature above 5°C, CT = continentality, DAMS = Detailed Aspect Method of Scoring and MD = moisture deficit.

Location	Glenbranter 56°07′38″N, 5°03′16″W	Chiddingfold, Plaistow 51° 03’ 49”N, 0° 35’ 19”W
Elevation/ Aspect	250m/ south east	60m/ south west
Exposure	Open to south east	Open to most directions
Slope	South east	Gentle to south west
Geological formation/ soil	Morainic drift/ brown earth	Weald clay/ clay
AT5	1331.1	1935.1
CT	4.4	10.2
DAMS	12.3	11.4
MD	106.3	209.7
Summer Rainfall (mm)	991.1	351.2
Winter Rainfall (mm)	1522.3	463.8

For the trees at Chiddingfold the crown projection was also calculated by measuring distances from stem to canopy edge and bearings at eight points using a method developed by Forest Research (2001). The first step in this method was to mark out the projection (area) of the crown by defining its extent as precisely as possible using eight marker posts. The distance and bearing from magnetic north to these posts was then measured using a tape and Suunto KB-14 compass respectively. In calculating distance from the tree stem to the canopy edge, half of the stem diameter was added in as the measurement was taken from the stem surface, not stem cross sectional mid point. The area of the crown projection was calculated by summing the area of the eight triangles, each defined by the tree stem and two marker posts. The following equation was used to calculate the area of each triangle:

$A = \sin \alpha(a \cdot b)/2$

Where a is the distance to one pole, b is the distance to another and α is the angle between the two poles.

To convert each tree's growth into a per hectare basis, the crown projection (m^2) was used to determine an appropriate stocking (stems ha^{-1}). This was undertaken using the following equation:

Stocking = 10,000/ crown projection

For the two trees at Glenbranter stocking was estimated at 871 stems ha^{-1}, based on stocking of trees in seven 0.01 ha plots measured when TLS measurements were taken.

The tree MAI, CAI and cumulative volumes of the individual trees were multiplied by the stocking to convert growth and volume to a per hectare basis. Curves were then fitted using the curve fitting function in SPSS v19 using the data directly or where applicable asking a natural logarithm. Functions were selected on the basis of high R^2, low standard error and a visual assessment of fit.

Results

Study 1: Validation of volume functions

The data for dbh, height and stem volume were divided into three groups; the six year old trees from Woodhorn (n=473), the ten year old trees from Thoresby (n=25) and the combined 27 and 43 year old trees from Chiddingfold and Glenbranter (n=12).

The median residual of estimated tree volume against actual tree volume was calculated and plotted against stem volume. In general the AFOCEL function provided a better fit (Table 5.6), but for very small trees present on the Woodhorn site, it was clear that the AFOCEL function was not appropriate; estimated volume for small trees being negative. However if trees below 10cm dbh were excluded the AFOCEL function also provided a better fit for tree volumes at Woodhorn. The Shell function consistently underestimated tree volume in all cases. The residuals plotted against tree volume are shown in Figures 5.2 to 5.4.

Linear regressions of measured stem volume (y axis) against predicted stem volume (x axis) for each equation was performed, as described in Sileshi (2014) for each of the four data sets and the R^2 calculated as a measure of goodness of fit. A description of the parameters a and b, the R^2 of the regressions are shown in Table 5.7 (Statistical supporting data is presented in Appendix 8.1).

Table 5.6 Median residuals for Shell and AFOCEL functions. [a] Function produces negative volume values for small trees.

	Shell function	AFOCEL function
Woodhorn (all trees, n=473)	26.4%	34.4%[a]
Woodhorn (trees dbh>10cm, n=126)	20.5%	9.1%
Thoresby	14.1%	-4.4%
Chiddingfold/ Glenbranter	22.6%	1.2%

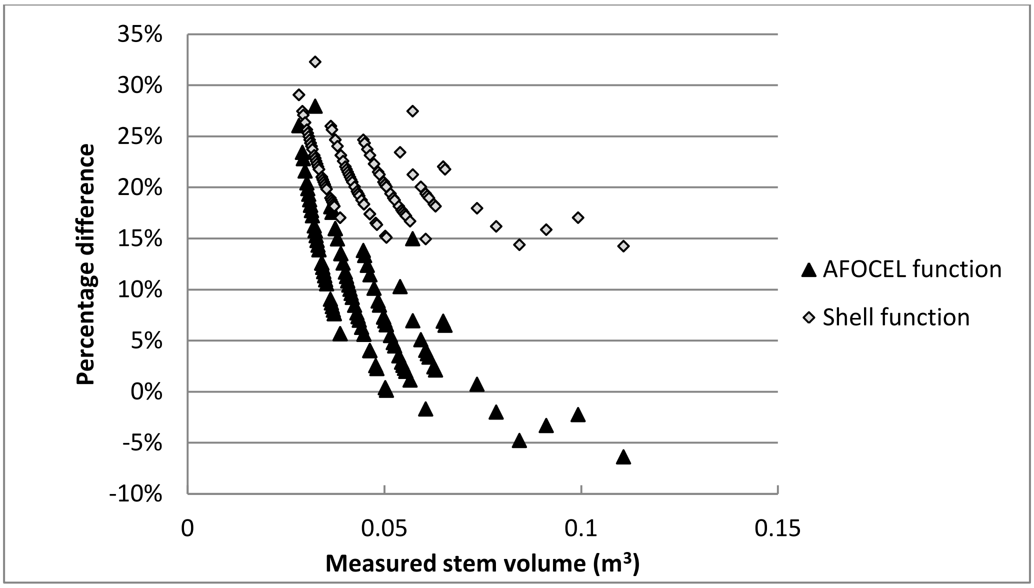

Figure 5.2: Residuals for AFOCEL and Shell functions against stem volume for Woodhorn

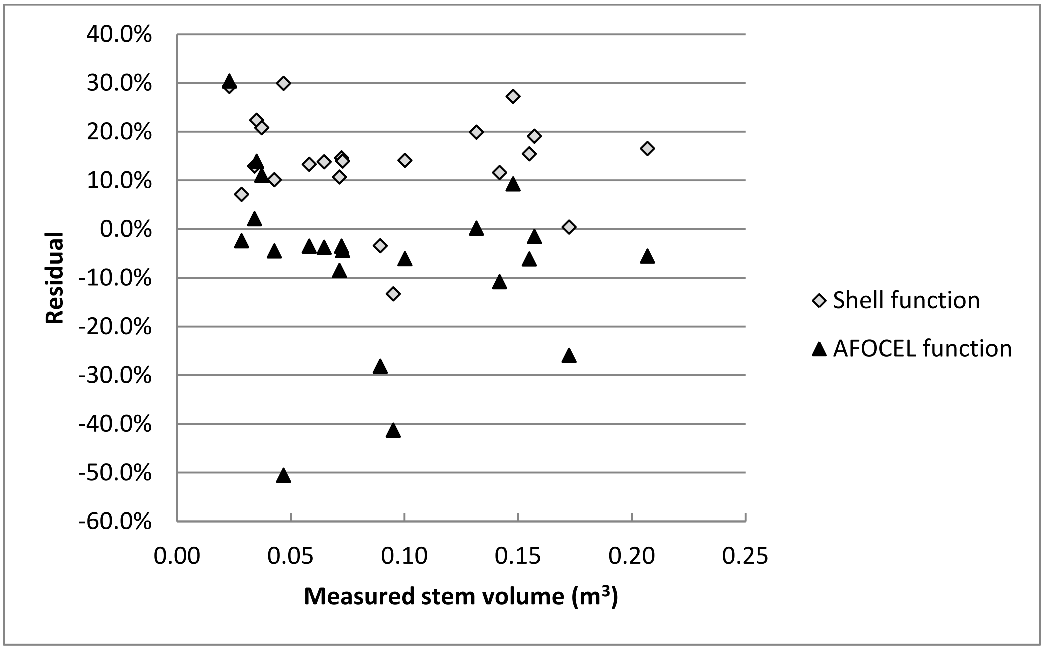

Figure 5.3: Residuals for AFOCEL and Shell functions against stem volume for Thoresby.

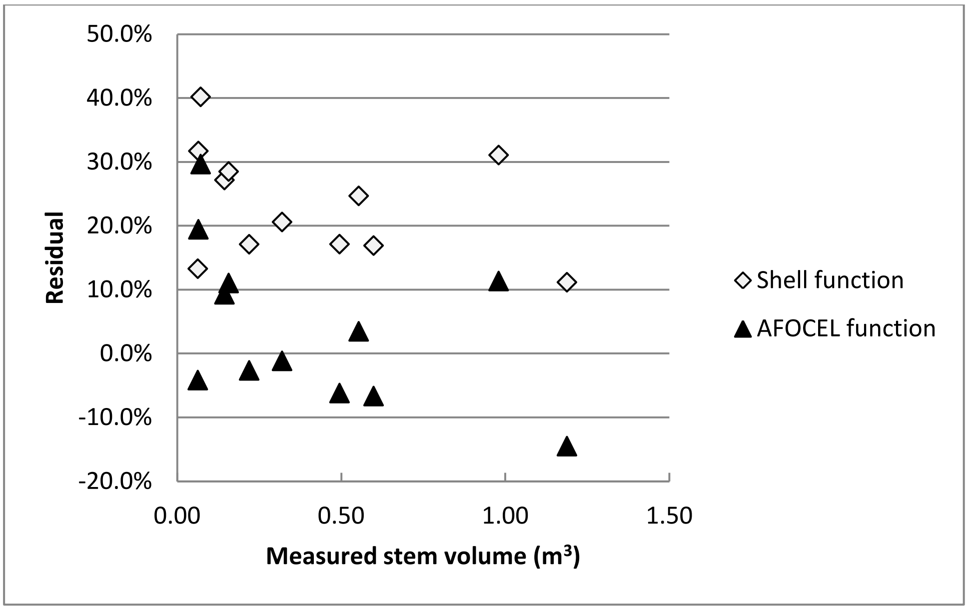

Figure 5.4: Residuals for AFOCEL and Shell functions against stem volume for Chiddingfold/ Glenbranter.

Study 2: Developing a generalised growth function

Nonlinear regression of height against age was undertaken using four commonly used functions and the Richard's function was found to give the best fit in terms of high R^2 and low standard error (Table 5.8). A comparison with statistical data for the other curves tested is shown in Appendix 8.2. The curve derived from the Richard's equation is shown graphically in Figure 5.5, with the height curve from French plantations (FCBA 2012) superimposed.

Table 5.7 Parameters and R^2 for linear regressions of measured stem volume against predicted stem volume. Formula for the line is Y =bx + a.

Function	Site	Parameters		R^2
		a	b	
Shell function	Woodhorn (all trees, n=473)	0.020	1.185	0.957
	Woodhorn (trees dbh>10cm, n=126)	0.004	1.132	0.992
	Thoresby (n=25)	0.003	1.111	0.975
	Chiddingfold/ Glenbranter (n=12)	0.230	1.191	0.977
AFOCEL function	Woodhorn (all trees, n=473)	0.007	0.916	0.978
	Woodhorn (trees dbh>10cm, n=126)	0.090	0.875	0.992
	Thoresby (n=25)	0.004	0.891	0.952
	Chiddingfold/ Glenbranter (n=12)	0.028	0.920	0.977

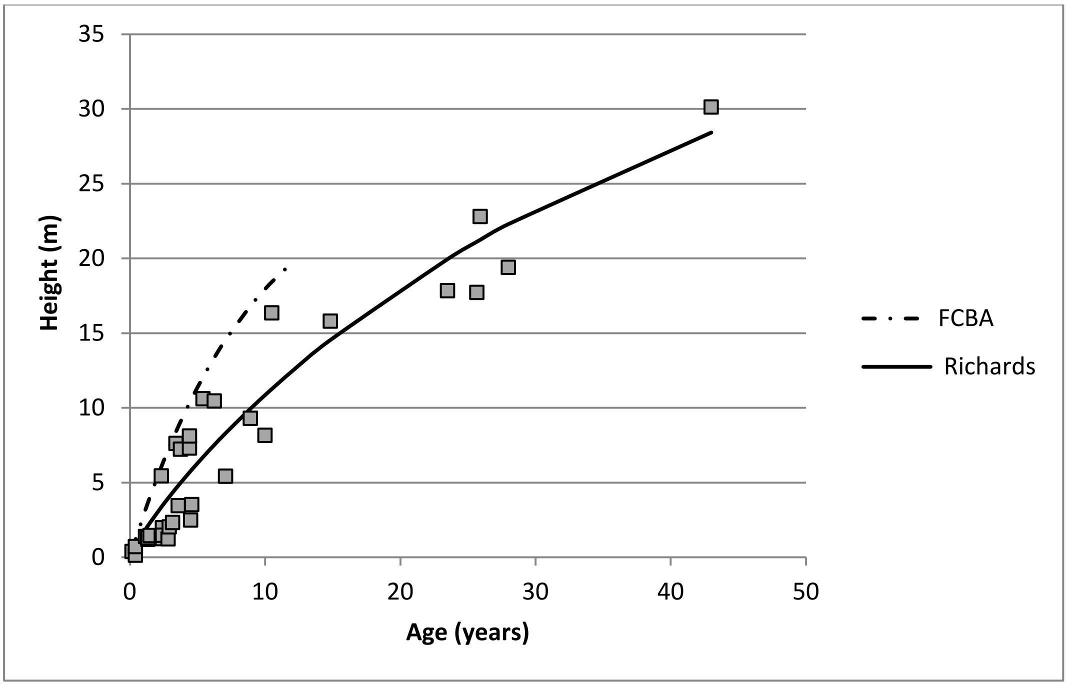

Figure 5.5: Mean plot heights by age with fitted Richards' function and in comparison the FCBA height curve (FCBA 2012). FCBA height function is based on trees up to 12 years old and so has not been applied to older trees.

Eleven types of function were used in regression of dbh against height and were compared through R^2 and standard error. Of these a linear relationship provided the best fit to the data, in terms of a high R^2 and lowest SEE (Table 5.8 and Figure 5.6). The statistical analysis is presented in Appendix 8.3.

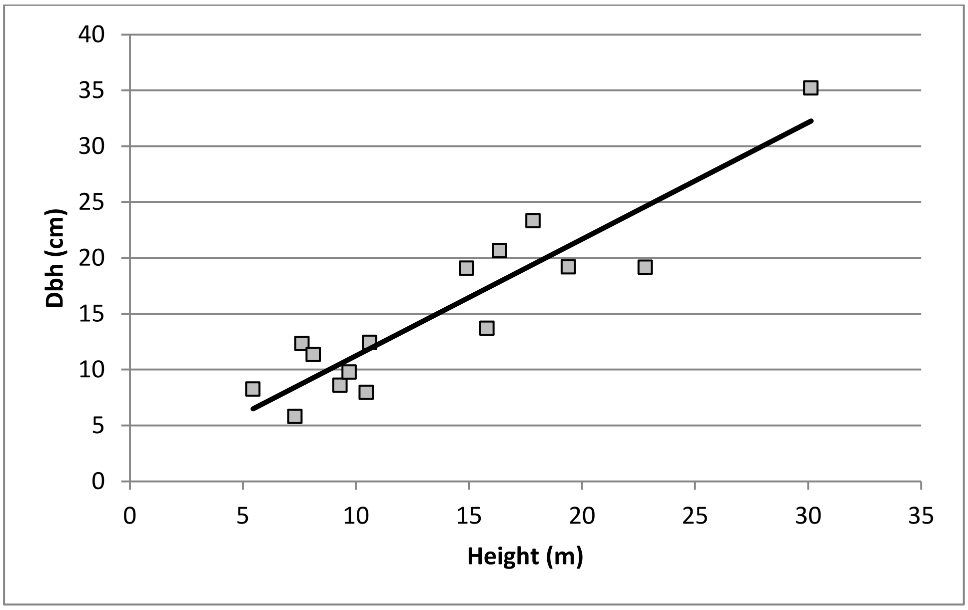

Figure 5.6: Relationship between dbh and height, with best fit line.

Using the two functions, height and dbh at ages up to 20 years were estimated and volumes for each age from zero to twenty years was calculated using the AFOCEL function. The standing volume curve using this approach is shown in Figure 5.7. Mean annual volume increment over a twenty year rotation was 16 m^3 ha^{-1} $year^{-1}$ and applying a specific gravity of 500kg m^{-3}, gives a mean annual dry weight increment of 8t ha^{-1} $year^{-1}$.

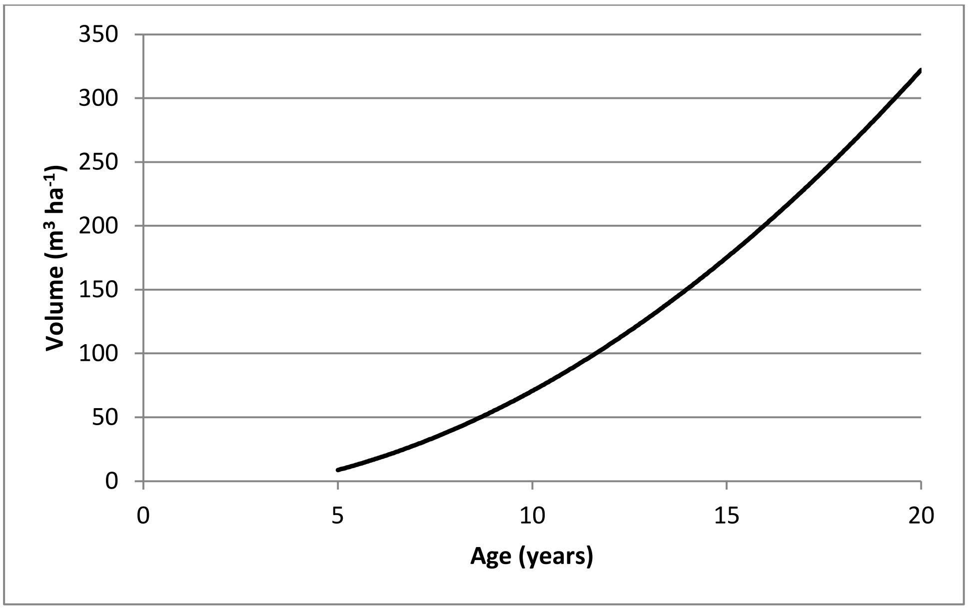

Figure 5.7: Predicted standing overbark volume by age, with tree volume calculated using dbh and height estimated from the age: height function and height:dbh function and volume from the AFOCEL function. Stocking was assumed to be a constant 1,350 stems ha^{-1}.

Table 5.8: Description of the best fit models for age and height and height and dbh.

x	y	Model	N	r^2	SEE	A	b	c
Age (years)	Height (m)	Richards	34	0.911	2.370	43.16	-0.022	0.851
Height (m)	Dbh (cm)	Linear* (y=a+b•x)	15	0.843	3.181	0.797	1.044	-

*Where Y is dbh and X is height and a and b are parameters for the model.

Study 3: Growth functions from stem analysis on trees from Chiddingfold and Glenbranter

One tree of the ten from Chiddingfold was excluded from the stem analysis, as the age determined from ring counts was much less than that of the known age of 28 years. Possible reasons for this are commented upon in the discussion. A summary of dimensions and growth variables for each of the ten trees is shown in Table 5.9.

Table 5.9: Growth variables at 28 years of age for the trees at Chiddingfold.

	Tree number									
	1	2	3	4	5	6	7	8	9	10
Dbh (cm)	36.2	10.6	19.7	15.4	11.6/ 9.6	11.2	25.4	11.9	1.7/ 9.9	26.8
Height (m)	29.3	14.3	23.8	16.1	18.0	15.8	23.5	11.0	17.2	25.2
Volume (m^3) ob	1.127	0.047	0.283	0.115	0.157	0.062	0.380	0.071	0.214	0.483
Volume (m^3) ub	1.062	0.044	0.271	0.108	0.148	0.056	0.363	0.067	0.199	0.464
MAI (m^3 ha^{-1} y^{-1}) ob	16.3	5.8	9.3	1.9		4.0	5.7	3.2	7.6	4.8
CAI (m^3 ha^{-1} y^{-1}) ob	27.2	5.4	10.3	1.9		2.6	3.6	3.3	6.7	4.3
Crown Projection (m^2)	23.25	2.75	10.46	20.07	11.24	5.02	22.79	7.61	9.34	34.84
Effective stocking (stems ha^{-1})	430	3632	955	498	893	1991	431	1313	1071	287
Volume (m^3 ha^{-1}) ob	457	161	259	54	140	11	159	89	213	133

Figure 5.8 shows height by age and the best fitting relationship was a Richard's function having highest R^2 and lowest SEE (Table 5.10). The statistical analyis is presented in Appendix 8.4. For most ages, height was found to be normally distributed (The output of a Shapiro Wilkes test is

presented in Appendix 8.5) so means and error bars are also shown in Figure 5.8 for ages where there were sufficient data.

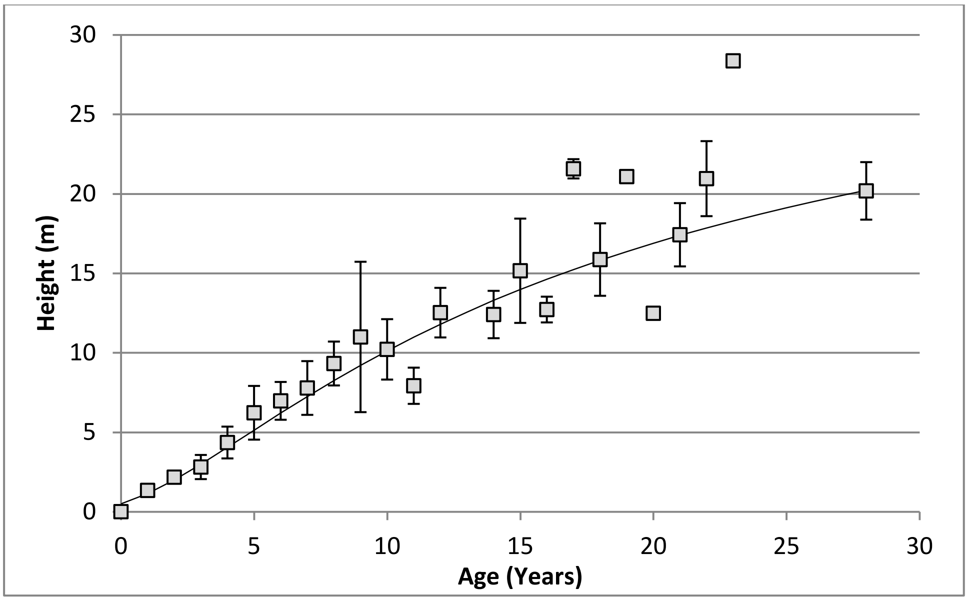

Figure 5.8: Height by age from stem analysis of Chiddingfold trees, with mean heights and error bars.

The relationship between dbh and height for trees at Chiddingfold is shown in Figure 9 and the equation for the best fit curve in terms of high R^2 and low SEE in Table 5.10. The statistical analysis is presented in Appendix 8.6.

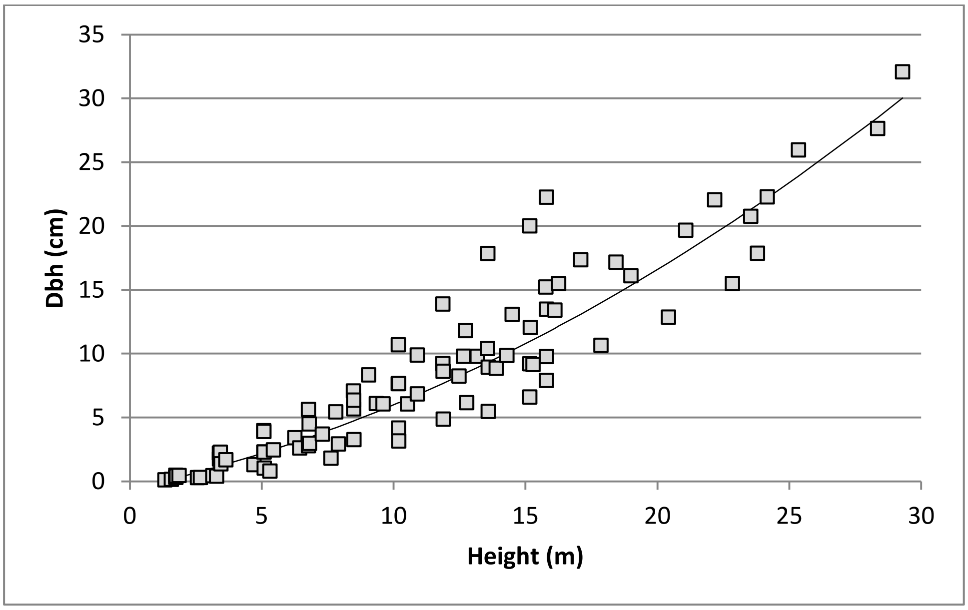

Figure 5.9: Dbh by height of Chiddingfold stem analysis trees, with best fit curve.

Shapiro-Wilkes tests showed that the distribution of MAI and cumulative volumes by age of the nine trees was significantly different from normal at some ages (Appendix 8.7 presents the Shapiro Wilkes test) and so median values for MAI and cumulative volume were used to generate growth curves on a tree and per hectare basis. Figure 5.10 illustrates the range across the nine trees for cumulative volume production per tree (m^3) and the median, while Figure 5.11 shows the range and median on a per hectare basis. The median CAI and MAI by age is shown in Figure 5.12.

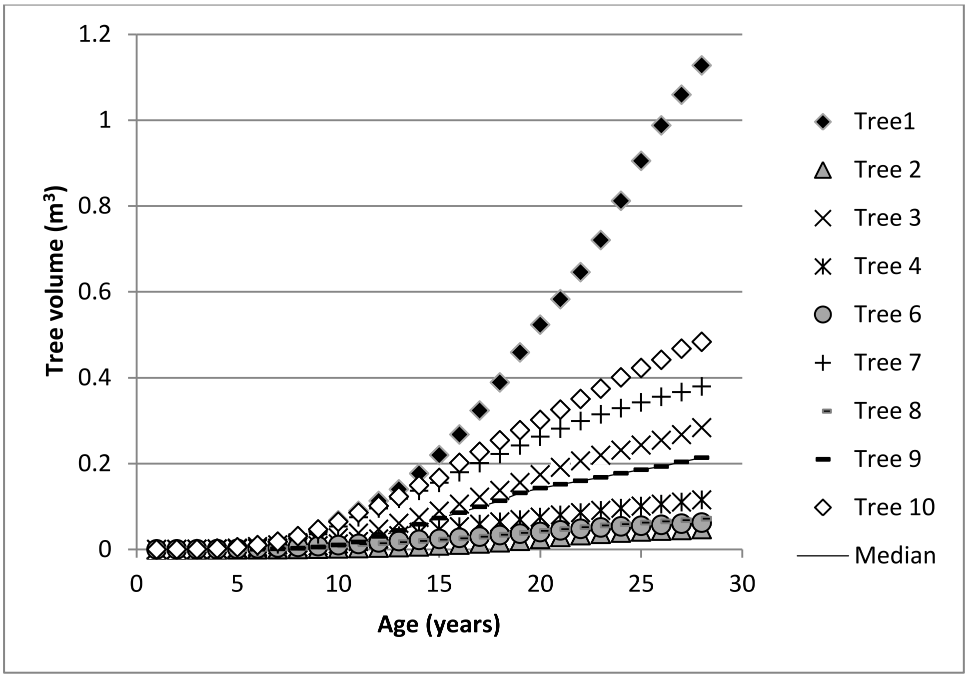

Figure 5.10: Overbark volume for each tree and the median by age at Chiddingfold

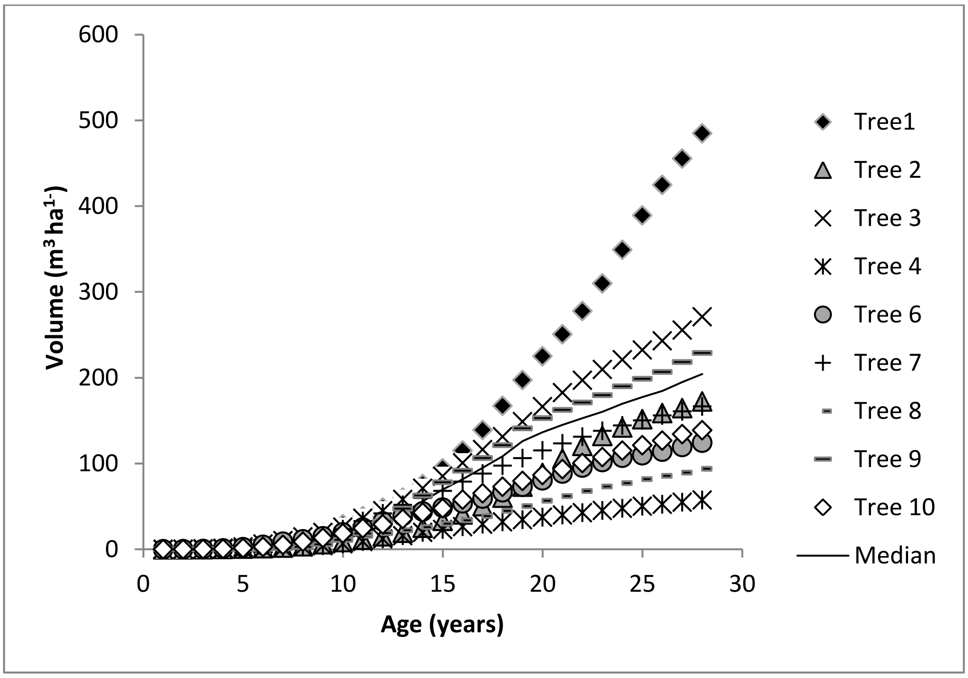

Figure 5.11 Overbark volume per hectare and the median by age at Chiddingfold.

The curves fitted to the age and cumulative volume and age and MAI on an overbark and underbark basis are shown in Table 5.10. The best fit curve was selected on the basis of high R^2 and low SEE; the statistical analysis is presented in Appendix 8.8 to Appendix 8.11.

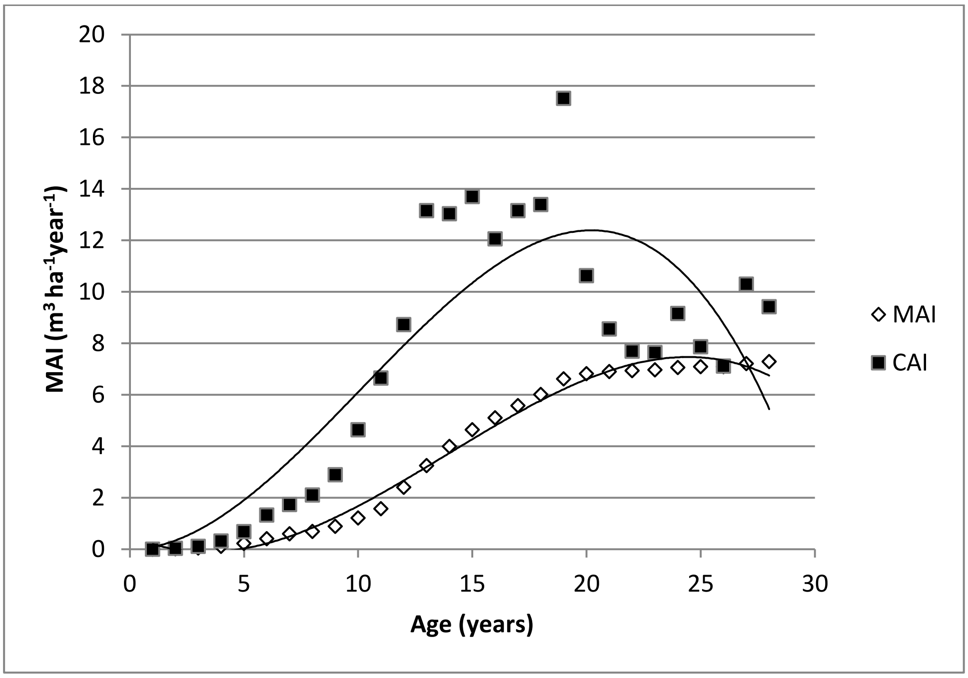

Figure 5.12 MAI and CAI by age of the median tree at Chiddingfold.

A similar approach was taken for developing growth curves for the two trees felled at Glenbranter. Figure 5.13 illustrates the relationship between height and age and the best fit Richards function based on high R^2 and low SEE (Table 5.11). A comparison of the statistical data for the growth functions for height and age is shown in Appendix 8.12. Figure 5.14 illustrates the relationship between dbh and height, while the best fitting function in terms of highest R^2 and low SEE is described in Table 5.11 and the statistical comparison of functions in Appendix 8.13. Cumulative volume on a tree basis and on a per hectare basis is shown in Figure 5.15 and 5.16 respectively. Table 5.11 describes the best fit models relating growth variables to age or height for Glenbranter trees. When fitting the curves three provided a particularly good fit in terms of R^2 and SEE, cubic, quadratic and power functions. However the quadratic one gave negative values of volume between age of 5 and 18 years. The power one was a poorer fit at older ages of greater than 30 years. The cubic function has none of these shortcomings. Graphs comparing these three functions for overbark and underbark volume and MAI are shown in Appendix 8.14 to 8.17.

Table 5.10 Description of best fit models relating growth variables to age for median Chiddingfold tree.

x	y	Model	N	R^2	SEE	a	b	c	d
Age (years)	Height (m)	Richards	99	0.762	3.392	30.051	-0.062	0.66	
Height (m)	Dbh (cm)	$y=ax^2+bx+c$	91	0.932	1.884	0.02	0.46	-0.614	
Age (years)	Volume (m^3ha^{-1}) ob	$y=ax^3+bx^2+cx+d$	28	0.997	5.070	-0.25	1.299	-10.493	17.690
Age (years)	MAI ($m^3ha^{-1}y^{-1}$) ob	$y=ax^3+bx^2+cx+d$	28	0.990	0.770	-0.002	0.067	-0.398	0.544
Age (years)	Volume (m^3ha^{-1}) ub	$y=ax^3+bx^2+cx+d$	28	0.996	4.651	-0.024	1.254	-10.240	17.427
Age (years)	MAI ($m^3ha^{-1}y^{-1}$) ub	$y=ax^3+bx^2+cx+d$	28	0.991	0.284	-0.002	0.065	-0.390	0.528

Volume and MAI curves are fitted for data at ages 5 years and above, except for volume underbark which was for data at ages 6 years and above.

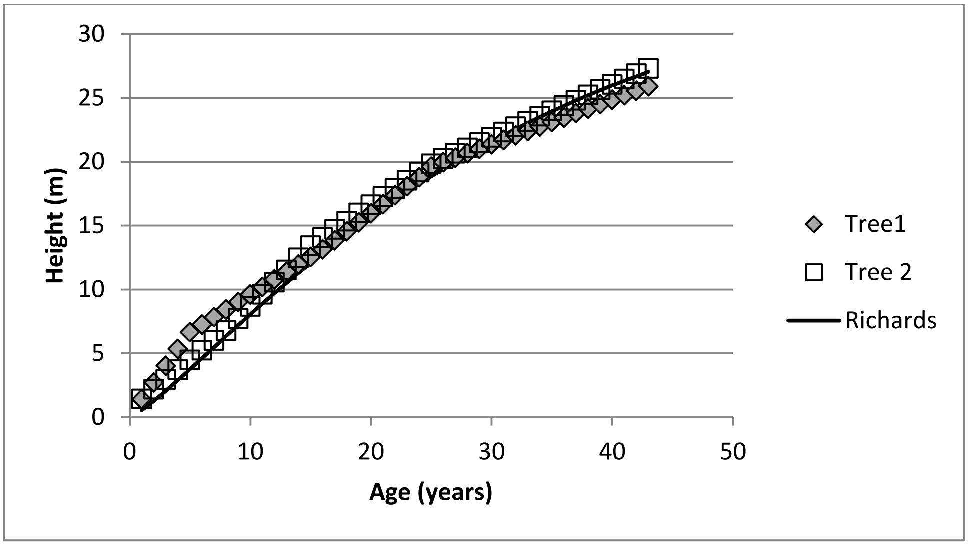

Figure 5.13: Height by age from stem analysis of Glenbranter trees.

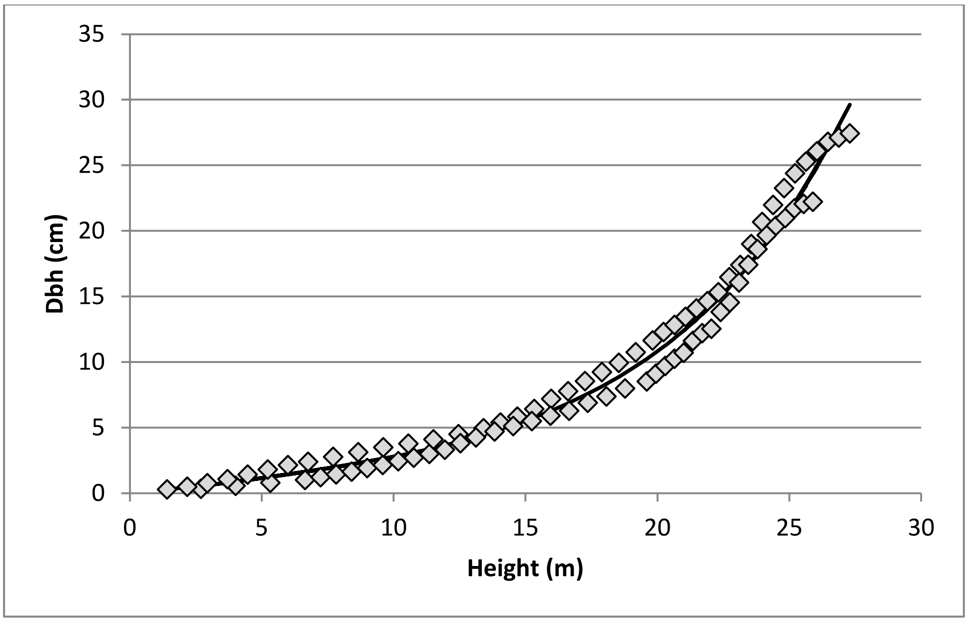

Figure 5.14: Dbh by height of Glenbranter stem analysis trees, with best fit curve.

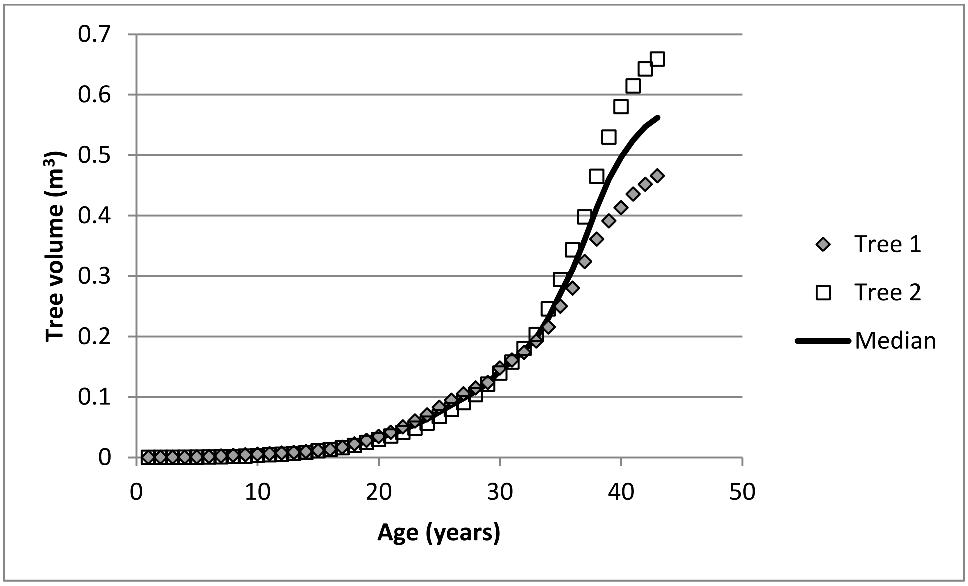

Figure 5.15: Overbark tree volume by age at Glenbranter

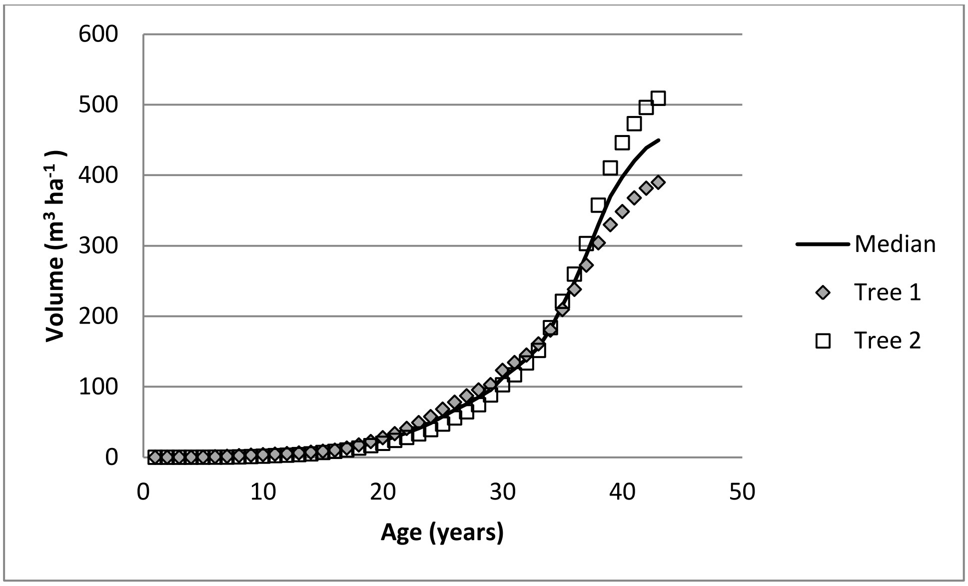

Figure 5.16: Cumulative volume ha^{-1} by age at Glenbranter.

Table 5.11 Description of best fit models relating growth variables to age or height for Glenbranter trees.

x	y	Model	N	R^2	SEE	a	b	c	d
Age (years)	Height (m)	Richards	86	0.995	0.558	37.007	0.027	1.101	
Height (m)	Dbh (cm)	$y=ax^3+bx^2+cx+d$	85	0.984	1.028	0.003	0.068	0.815	-1.290
Age (years)	Volume (m^3 ha^{-1}) ob	$y=ax^3+bx^2+cx+d$	43	0.994	12.470	0.013	-0.345	3.190	-6.224
Age (years)	MAI (m^3 ha^{-1} y^{-1}) ob	$y=ax^3+bx^2+cx+d$	43	0.992	0.338	0.00016	-0.00034	0.00708	0.0581
Age (years)	Volume (m^3 ha^{-1}) ub	$y=ax^3+bx^2+cx+d$	43	0.993	11.853	0.012	-0.327	2.934	-5.678
Age (years)	MAI (m^3 ha^{-1} y^{-1}) ub	$y=ax+bx^2+cx+d$	43	0.992	0.321	0.00015	-0.00018	0.00147	0.0583

Discussion

This study represents the first work to characterise growth curves of E. gunnii in the UK and the results are discussed below in four parts; [1], the validation of volume equations, [2], the development of growth curves, [3], a critique of the methods and [4] a discussion of the wider implications of the findings.

Study 1: Validation of volume functions

For trees of dimensions likely to be used for biomass, the AFOCEL volume function estimated volume of E. gunnii more precisely than the Shell function. This was predictable, as the function was developed using data from stands of E. gunnii and E. x gundal hybrids in France (AFOCEL 2003a), whereas the Shell function was a more general equation covering a range of commercial cold tolerant eucalypts in Chile (Purse and Richardson 2001), which were unlikely to include E. gunnii.

The residuals for estimates of stem volume from the six year old trees at Woodhorn (Figure 5.2, Table 5.6) showed an unusual distribution of the data. These data were obtained from scans using a TLS and it is likely that the curvilinear distribution of the data reflects the functions used to convert the data from the points identified by the TLS to stem dimensions. Both the AFOCEL and Shell volume functions underestimate the volumes determined through use of the TLS. For the ten year old trees at Thoresby, the Shell function consistently underestimated stem volumes, while the AFOCEL function provided a more balanced estimate (Figure 5.3, Table 5.6). The AFOCEL function estimated the volumes of larger trees more precisely than for smaller trees (Figure 5.3). The residuals for estimates of stem volumes for the combined Chiddingfold and Glenbranter trees, of 28 years and 43 years of age respectively is shown in Figure 5.4. The Shell function again underestimated the volume of all trees, while the AFOCEL function provided a better and more balanced estimate (Table 5.6).

Study 2: Developing a generalised growth function

The wide spread in the data (Figure 5.8) for height by age reflects genetic differences between the trees, variations in the quality of silviculture and the range of site conditions at which these data were collected. A Richards' function described over 90% of the variation in the relationship between age and height (Table 5.9). Diameter is more strongly influenced by growing space than height. Across the stands that provided the historic data, differences in initial spacing and subsequent mortality had resulted there being a wide range of growing space. This variation in growing space, and the small number of records of dbh make modelling the relationship between height and diameter imprecise. To narrow the range of growing space, only data from stands with initial stocking of between 1200 and 2500 stems ha^{-1} were used. Figure 5.6 shows the results based on mean data from 15 different measurements and a linear function explained 84% of the variation (Table 5.8).

Combining the age:height curve, the dbh:height curve and the AFOCEL volume function, volume growth was predicted (Figure 5.7) over twenty years. This period was used as for three reasons: it is close to the predicted 15 year rotation for E. gunnii grown for biomass (Hardcastle 2006) and for these unthinned stands that provided the data, competition was probably not overly intense, providing some indication of potential yield of managed stands. The volume growth curve gave a standing volume of 320 m^3 ha^{-1} at 20 years of age, giving a mean annual increment of 16 m^3 ha^{-1} y^{-1} or an estimated dry mass increment of 8t ha^{-1} y^{-1}. Growth of these trees was considerably slower than the intensively managed stands in France, where volumes of 200 m^3 ha^{-1} are achieved in 12 years (AFOCEL 2003a), compared with around 16 years from the British stands (Figure 5.7).

It is clear from the data mining exercise that there is considerable variation in growth between trees within stands and also between stands at different locations and grown under different intensities of silviculture. As such, the results from this study represent a first and highly generalised attempt at characterising E. gunnii growth under British conditions, based on a limited amount of data. At sites, such as Daneshill (Nottinghamshire) and the New Forest (Hampshire) a height of 10 m has been achieved at 5 or 6 years of age. At Daneshill part of this rapid growth is probably due to the intensive establishment methods used, such as planting the trees through biodegradable plastic sheeting, a technique to inhibit weed competition and the use of high nitrogen sewage sludge as a biofertiliser. At other sites, including the more northerly one at Glenbranter the same height was only reached in ten years.

Study 3: Growth functions from stem analysis on trees from Chiddingfold and Glenbranter

A Richards function was selected as best fit for height growth at Chiddingfold (Figure 5.8) and Glenbranter (Figure 5.13). Polynomial functions provided a good characterisation of the relationship between height and dbh at Chiddingfold (Table 5.10) and at Glenbranter (Table 5.11).

Characterising growth proved more difficult, although good fit functions were developed for cumulative volume and for mean annual increment (Table 5.10 and Table 5.11). For these variables the best-fit functions gave negative values in the early years of growth and so they are only applicable to trees above six years old. A wide range of functions were applied to CAI data and also log transformed CAI data, including equations recommended in FAO (1980). However it was not possible to obtain a function that adequately represented growth due to the rapid decline in CAI in the trees' later years, demonstrated by very narrow ring widths on the stem discs. This is likely to have been because the stands have not been thinned and so would be atypical of trees in managed stands.

The trees at Chiddingfold exhibited a considerable variation in growth rate, reflecting the high levels of competition in the unthinned stand. The dominant tree, tree1 had achieved an overbark stem volume of over 1 m^3 in 28 years, whereas the overbark volume of the smallest tree was only 0.047 m^3 (Table 5.9). The stem volume and increment data was not normally distributed and so the median rather than means of these variables was used to develop growth curves. For each tree from stem volume was converted to a volume per unit area using crown projection.

Trees at Chiddingfold have grown relatively slowly, with 200 m^3 ha^{-1} being achieved at 28 years old (Figure 5.11), giving an MAI of 7 m^3 ha^{-1} y^{-1}. EMIS was used to estimate growth of alder (Alnus glutinosa), predicted to be the most productive broadleaf at the site, growth of which was estimated at a MMAI of 10 m^3 ha^{-1} y^{-1}, while the most productive conifer, western red cedar (Thuja plicata) was predicted to achieve a MAI of 16 m^3 ha^{-1} y^{-1}. At 30 years old, the MAI of alder was estimated to be 9.3 m^3 ha^{-1} y^{-1}, while for western red cedar at 31 years old it was 10.9 m^3 ha^{-1} y^{-1} (Forestry Commission 2009a). There would appear to be more productive trees than E. gunnii that can be grown at Chiddingfold. Only two trees were felled at Glenbranter for seed collection and were then available for stem analysis. A sample from seven 0.01 ha plots and 47 live trees gave a quadratic mean dbh of 30.8 cm and a mean height of 29.7 m. The two trees used for stem analysis had a quadratic mean dbh of 27.2 and a mean height of 26.6 m, so had a smaller quadratic mean dbh and height than the trees in the sample plots and so may underestimate growth of the stand as a whole. The trees at Glenbranter had reached an MAI of 4.5 m^3 ha^{-1} y^{-1} at age 30 years and 11.4 m^3 ha^{-1} y^{-1}at age 43 years.

The data also reinforces the need for good silviculture and maintenance. The stands at Chiddingfold and Glenbranter are unthinned. The stem analysis data supports the assertion that growth had slowed to almost zero in later years due to intense intra-stand competition. Furthermore, the initial growth of many of the older stands is likely to be slower that its potential due to lack of maintenance. The cumulative volume starts to flatten off at Glenbranter later than at Chiddingfold possibly due to a lesser degree of competition as the stocking of the stand at Glenbranter is less. The patterns of CAI and MAI suggest that longer rotations than those suggested under short rotation forestry will maximise volume as MAI was still increasing in the final year before the trees were felled; 28 years at Chiddingfold and and 43 years at Glenbranter. The MAI and CAI for the median tree is shown in Figure 5.12. For all but one of the nine trees MAI was still increasing at 28 years, the age at which they were felled. For the remaining tree, MAI peaked at 27 years. For the four largest trees CAI peaked at between 19 and 25 years of age, whereas for the two smallest trees it peaked between 14 and 20 years of age. In all trees CAI dropped considerably in the latter years, probably due to high competition in the unthinned stand. For the two trees felled at Glenbranter and MAI was still increasing at age 43 years.

Critique of the methods

The study was hampered by the lack of data available on growth of E. gunnii in the UK, with there being very few sites planted across the UK and then each site providing only a limited amount of chronological data. There were more data for tree height and the use of dbh data was complicated by the wide range of spacing employed across the plantings. To reduce this variation, data from a restricted range of spacing was used to determine the relationship between dbh and height.

Stem analysis is a common approach to obtaining growth data from forest trees and stands and was the only method to obtain annual growth data across a time period of a rotation. There were some considerable constraints to the application of this method. A major shortcoming is the small number of trees used in the study, especially from the site at Glenbranter. Furthermore, the lack of thinning meant that there was much more variation in the growth of the trees than there would have been in a managed stand.

The stem analysis method itself was hampered by the difficulty in discerning annual growth rings in some cases. This was due to three factors:

1. The lack of dormancy over warm periods in winter means annual growth is less defined than in most temperate trees.

2. The diffuse porous wood structure exhibited by E. gunnii made definition of rings less clear than in ring porous hardwood species.

3. The narrow ring widths or missing rings in later years of growth, due to high competition between trees in the unthinned stands at Chiddingfold and at Glenbranter.

Many temperate eucalypts display more or less annual rings, although a study of ageing trees of Eucalyptus diversicolor showed that this pattern was most reliable in dominant trees (Rayner 1992 in Von Platen 2008). The lack of thinning and rapid growth meant that, to a degree most of the trees sampled were under considerable competition in their later years. Trees that are suppressed are known not to produce annual rings in lower portions of the stem, resources being concentrated on height growth, rather than diameter (Pallardy 2007). In suppressed trees it is likely that the determination of annual rings was most reliable for the earlier years of growth, when the trees were under less competition. One suppressed tree from Chiddingfold was omitted from this study as the ring count at the base of the tree did not correspond to the known age of the tree. Ring counts from the discs cut up the tree stem were used to identify height attained as the tree developed. Comparison of the height curves based on the mined data (Figure 5.5) and on stem analysis (Figure 5.8 and Figure 5.12), showed them to be similar, suggesting that the data from the stem analysis was reliable.

Wider implications of the findings

The trees in this study have grown more slowly than growth rates estimated some earlier studies (Kerr and Evans 2011, Cope et al 2008). The data reported also suggest that for yields to be maximised intensive silviculture is necessary. At Daneshill, stands of E. gunnii achieved a height of over 10 m at five and a half years of age, a results of intensive establishment using complete cultivation and the use of a plastic mulch to control weed competition and sewage sludge as a nitrogen rich fertiliser. In contrast it took more than ten years at Glenbranter for trees to reach the same height (Table 5.4). There are however influences on growth as trees at Thoresby were relatively neglected, yet attained a height of over 16 m in 10 years.

High mortality of E. gunnii in many stands has a major impact on potential productivity and if planted on a greater scale then those sites most suited to E. gunnii need to be identified. In the mid Pyrennes in France a zonation of sites by climate and soils was developed to predict the risk of cold damage to E. gunnii and E. gundal (FCBA 2010). Across France, four zones were defined in terms of the suitability of climate and soils, based on tolerable minimum thresholds of mid-winter temperatures and the risk of lime induced chlorosis. Zonation was based on the average number of days when minimum mid-winter temperatures of -12^{o}C for E. gundal and -18^{o}C for E. gunnii were exceeded. A similar approach could be adopted to identify sites appropriate for planting E. gunnii in the UK, which could follow that of the maps produced for Nothofagus nervosa in Hardcastle (2006). The risk of high mortality of eucalypts would be further reduced by the use of genetic material that was well adapted to UK conditions.

Conclusion

The small area of planting of E.gunnii in the UK and a lack of time series data makes predicting growth rates difficult. It is clear that high productivity is possible from E. gunnii in the UK, but rarely achieved in practice. The MAI at the Chiddingfold was 7 m^3 ha^{-1} y^{-1} at 28 years old yet much more rapid growth has been experienced at other sites, such as at Daneshill. Part of this difference is likely to be due to intensive silviculture, but there are examples of rapid growth of stands even when less intensive silviculture is applied, such as at Thoresby Hall Estate, also in Nottinghamshire.

This study was hampered by the small sample of trees available for stem analysis, the difficulty in some cases of identifying annual rings and the narrowness of recent rings, due to inter-tree competition in unthinned stands. However it provides the first characterisation of growth of E. gunnii in the UK.

Acknowledgements

This study could not have been completed without the help of many people. Dr Richard Jinks kindly provided all files of experiments using E. gunnii at Forest Research, while Ted Woodisse sent data from the trials established at Daneshill by Nottinghamshire County Council. Dr Eric Cassela of Forest Research provided TLS data on stem dimensions of E. gunnii from a study he conducted at Woodhorn, while Tim Hill and George Clarke kindly allowed measurement of trees at Thoresby Hall Estate. The trees used for stem analysis were felled under the supervision of Mark Oram and Carina Convery of Forest Research, while Carina also organised processing some of the stem discs with her colleague Colin McEvoy. Site information on Glanbranter was kindly supplied by Fraser MacDonald of Forestry Commission Scotland. Finally the authors would like to acknowledge funding for some of the felling and measurements of trees for stem analysis from the University of Cumbria's Research, Scholarship and Development Fund.

Chapter 6 Discussion and Conclusion

There were three main objectives in this study each with two research questions. These comprised:

1. To identify the species and provenances of eucalypts most suitable for biomass production in Great Britain
   - Which are the eucalypt species that are sufficiently productive to be an industrial source of biomass and can survive climatic extremes of the UK?
   - Are there particular provenances that are superior in terms of growth and survival?

2. To develop volume and biomass functions for E. gunnii and to estimate yields and patterns of growth for E. gunnii.
   - Do any of the current volume functions for cold tolerant eucalypts reliably predict volumes of UK grown E. gunnii?
   - What is the pattern of growth in E. gunnii and at what age can increment be maximised?

3..To compare growth of eucalypts with other promising SRF genera.

- Is the production of biomass from eucalypts superior to that of other genera?
- What are the risks associated with using eucalypts compared with other genera?

These are discussed in the following sections.

6.1 To identify the species and provenances of eucalypts most suitable for biomass production in Great Britain.

There are individuals and stands of eucalypts across Great Britain that have survived and been productive over several decades. However the patchy coverage, small extent of plantings and lack of records makes matching species and origins to site imprecise. Climatic requirements have been defined for a number of eucalypt species. Booth and Pryor (1991) used information on natural distribution and where species had successfully been established in plantations to define the climatic requirements of 21 species, including some with potential for planting in the UK. However these profiles provide only a very broad description of areas that are climatically suitable and fail to consider the level of variation that can be tolerated and response to extreme events.

A more sophisticated approach has been adopted in France, where number of days below -12^{o}C over a fifty year period and soil type was used to zone areas in terms of suitability for planting E. gunnii and the E. x gundal hybrid (AFOCEL 2010). The lower potential for planting eucalypts in Britain does not warrant such a costly approach but some means of identifying suitable sites was required. Ray (2005) developed criteria for identifying sites that are suitable for SRF in general that defines suitable sites as having AT of above 1200 day degrees, being sheltered (DAMS <14), with fertile soils (medium, rich or very rich) and where there are not severe moisture deficits. For frost sensitive genera such as Eucalyptus and Nothofagus it was also recommended that a guide developed by Murray, Cannell and Sheppard (1986) be used to restrict planting to sites where the 50 year absolute minimum temperature is above -14^{o}C. When these climatic and soil constraints are applied it is the south west of England and lowland and coastal areas of Wales that are most suitable.

While the criteria provided by Ray (2005) gives a view of the general areas of Britain where eucalypts might best be planted, there is also a need to define the species and origins that will be most productive on particular sites. There were two research questions in this study that related to the identification of origins suitable for planting in Great Britain:

1. Which are the eucalypt species that are sufficiently productive to be an industrial source of biomass and can survive climatic extremes of the UK?
2. Are there particular provenances that are superior in terms of growth and survival?

The following section relates to addressing these questions through an examination of the potential of particular species and a discussion of the limited information on superior origins identified of some species.

Species and origins that could provide a source of industrial biomass

While a priority must be defining sites and origins that are suited to planting eucalypts, this has proved problematic for a number of reasons:

- There are insufficient stands of eucalypts across the UK to be able to precisely define site suitability in term of climatic and soil characteristics, even for the more commonly planted species.
- For many of the private stands that exist there are poor records of origin, establishment techniques and other silvicultural interventions.
- The Forestry Commission trials established in the 1980s and across a broad range of sites were neglected for several decades. During this time self thinning and other avoidable mortality has taken place, making identification of the suitability of species and origins to particular sites imprecise.
- The eucalypts planted in the latest set of trials established across Great Britain in 2009, bore the brunt of the winter of 2009-2010, which was the most extreme in thirty years (Prior and

Kendon 2011). With climate change it is not clear whether such extreme events will become more or less frequent.

The review by Evans (1986) of initial results of those trials established in the early 1980s identified that only a limited number of the species and origins tested could survive the extremes of cold weather in the UK. Furthermore, there are data from trial plantings of eucalypts in Ireland which were established in the 1930s and have survived and attained large dimensions (Neilan and Thompson 2008). However, while it is recognised that while high potential yields can be realised using eucalypts, under conventional forestry management in the UK these are often not achieved (Kerr and Evans 2011).

The early series of Forestry Commission trials, established in 1981 were subjected to the extremely cold winter of 1981/82 and this eliminated a large number of origins from consideration for production forestry (Evans 1986). As such, the later trials, established up until 1985 focused on the most cold-tolerant origins (Evans 1986). The network of trails established in the 1980s provided some indication of the climatic limits of the more hardy species. For this study, the few trials that were identified as being in reasonable condition were assessed. These showed that there are eucalypts that have survived and grown productively over periods of several decades in specific locations in southern England. Results from these trials are somewhat confounded by self thinning and windthrow due to the tight initial spacing and a lack of maintenance. This created patchy survival and also increased mortality above what would have been achieved with timely management.

Much of the research on cold tolerance of eucalypts has focused on using frost chambers or laboratory based methods to examine damage (eg Harwood 1980, Tibbits and Reid 1987, Raymond et al 1992, Sheppard and Cannell 1987). A study with more practically applicable results has been undertaken by Black (unpublished data) in Ireland has shown that resistance to cold varies across eucalypt species and is a combination of absolute cold-tolerance and the pattern of acclimation to cold (seasonal variation in lethal temperatures for 50% of the shoots). The ranking of cold-tolerance produced by combining these factors differed from using minimum temperatures alone. When using this measure the most cold-tolerant species was E. rodwayi, with E. glaucescens and E. subcrenulata being more cold-resistant than E. gunnii. The least resistant species was E. nitens.

Table 2.4 described the characteristics of eucalypts with potential for production forestry in the UK, the information collated from a number of sources. The literature review and the results of the assessments of trials for this study have refined that list. The species discussed in the following section are considered to have the most potential as a source of biomass. Where superior origins can be identified these are also described.

Eucalyptus gunnii

A species of eucalypt, that has exhibited particular resistance to cold is Eucalyptus gunnii (Booth and Prior 1991, Evans 1986), with some individuals still present that survived temperatures as low as minus 23°C at a trail a Wark, near Kielder (Evans 1986). E. gunnii proved to be more resistant at a trial in Cumbria to the extreme cold, (the minimum grass temperature during their first winter being-17°C) than Eucalyptus nitens, but much less hardy than the naturalised and native broadleaved trees at the trial at Newton Rigg (Section 4.2). Furthermore, a recent study comparing the drought tolerance of E. gunnii and E. pauciflora, showed that although E. gunnii was found in wetter areas it displayed greater physiological drought tolerance. This was considered an adaptation to withstand root death due to anaerobic conditions from waterlogging (Sanger et al 2011). A considerable constraint to planting is the palatability of E. gunnii (Neilan and Thompson 2008) which was confirmed by observations from the trial at Newton Rigg, where E. gunnii; was damaged extensively during winter in particular, by roe deer and hares.

E. gunnii is known to exhibit considerable genetic diversity, a reflection of the variation in climate across its natural environment (Potts 1985, Potts and Reid 1985a, Potts and Reid 1985b). The Forestry Commission trials assessed in this study did not include E. gunnii, but previous work has identified that central Tasmanian origins, and in particular Lake MacKenzie provenances exhibited superior growth and survival (Evans 1986, Cope, Leslie and Weatherall 2008). However it is not only the considerable variation at the provenance level that is of interest as previous work has show that there is much variation in cold-tolerance between individuals within provenances or populations (Evans 1986).

Furthermore, E. gunnii of good stem form exist in several plantings in Britain (Purse and Richardson 2001). In France selection of cold-tolerant clones of E. gunnii of superior form, rather than vigour has been an approach adopted to develop plantations in the Haut Pyrennes in France (Purse and Richardson 2001, AFOCEL 2007). A small plot of material from the French programme was planted at Thoresby Hall Estate in Nottinghamshire. While not the most rapid growing of the E. gunnii origins on the site, exhibited consistent and good stem form. The French breeding programme also developed the E. gundal hybrid, a cross between the cold tolerant E. gunnii and E. dalrympleana which has faster growth and better stem form than the E. gunnii clones (AFOCEL 2006). A clonal approach to tree improvement of eucalypts was started in the UK in the 1980s, focused on developing a clonal population of particularly cold-tolerant individuals, those that had survived at least -19°C (Evans 1986) but was subsequently abandoned.

Given that it is difficult to obtain seed from Lake MacKenzie a strategy may be to select the best trees from superior stands of E. gunnii from across the UK and exploit them either through collecting seed or through vegetative means. The considerable variation within provenances in E. gunnii, also supports the strategy of selection of genetic material from individuals within better adapted provenances. Eucalypts are unlikely to be extensively planted over a large area of the UK, and so a seedling rather than vegetative propagation based approach to tree improvement may be more appropriate in terms of cost and complexity (Griffin 2014).

Eucalyptus subcrenulata/ Eucalyptus johnstonii

Of the origins of E. johnstonii and the closely related, E. subcrenulata planted at Haldon Forest in Devon, after 28 growing seasons, E. subcrenulata showed most promise (Table 3.13). Mount Cattley origins performed best and this is a relatively low altitude population for the species and it achieved over 62% survival, a dbh of over 30cm and height of over 21m. A complication in terms of using this origin in bulk seedlots is the significant differences in performance of seedlots from different mother trees. The plots containing Mount Cattley, Tasmania origins could however provide a useful source of seed for further experimental plantings of this species and selective thinning could release superior trees. Martin (1950) identified E. subcrenulata as being a species with promise, while Evans (1986) identified central or southern Tasmanian origins of the species as having potential for producing quality timber in the milder south west areas of England. The findings of this study support Evans' (1986) recommendation. The closely related E. johnstonii has been identified as having potential from trials in Ireland (Neilan and Thompson 2008) and so may be worth investigation, although survival was poor at the trial at Haldon Forest in Devon (Table 3.11).

Eucalypts delegatensis

A further species that could provide quality timber in south western England is E. delegatensis, The largest trees at the Haldon trial were of this species, but in general survival was poor with Tasmanian origins performing best (Table 3.13). One origin, collected at 1200 m altitude from a single mother tree from Ben Lomond in Tasmania, combined excellent growth with good survival of over 48% (Table 3.15). This was one of the most cold hardy provenances in early (5 year) assessments, but some mainland Australian origins showed good cold tolerance and also some other Tasmanian origins from high altitude areas of the central plateau (Evans 1986). E. delegatensis is one of the most important hardwood species in Australia, producing construction timber and pulp (Boland and Moran 1979) and so could have potential as a timber tree on warmer sites in the UK. From the assessment at Haldon, it is recommended that collections from superior trees of high altitude Tasmanian provenances be used if this species is to be planted in southern England.

Eucalyptus coccifera/ Eucalyptus nitida

E. coccifera and E. nitida, form an altitudinal cline, with E. coccifera being found at higher altitudes (Williams and Potts 1996). These species exhibited poor survival at the trial at Haldon Forest, although E. coccifera performed better (Table 3.13). The poor survival contradicts the experience at a 1953 trial of E. coccifera at Truro in Cornwall (Evans 1980a, Evans and Brooker 1981, Purse 2009a) and also earlier assessments of the trial in 1993 and 1995 showed 60% survival of the two species combined. The conflicting evidence suggests that these species may continue to be worth consideration. Purse (2009a) noted that the form of the E. nitida at Truro was excellent, especially compared with some E. gunnii also present and that natural regeneration of E. nitida was occurring at the trial. In Ireland, a constraint to planting E. coccifera has been the slow growth in the nursery (Leslie 2013).

Eucalyptus perriniana

E. perriniana exhibited good survival (Table 3.6) and growth in two of three trials assessed in southern England in this study. In its native habitat this species grows as a malee or small tree (Tasmanian Government 2003), yet at the trials it had grown into medium sized trees of median height 16m and maximum height of 24 m and with a single stem. If the wood is suitable for biomass this species may have potential in southern areas of Britain, although there are other species of eucalypts likely to grown more rapidly under similar conditions. From the analysis of the three snow gums trials the origin from Smiggin Holes (origin 302) performed best (Figure 3.4).

There are other species that were described in Table 2.4 but which have limitations to their adoption as a source of biomass. These comprise E. nitens and E. pauciflora:

Eucalyptus nitens

At a number of trials and small plots the Eucalypts nitens growth was exceptional, estimated at over 30 m^3 ha^{-1} y^{-1} (eg Table 3.7). At five years of age, Evans (1986) identified high altitude Victoria provenances as being particularly hardy However, it is clear that this species is insufficiently cold hardy to be planted in any but the least frosty parts of Britain (Evans 1986, Bennett and Leslie 2003). A line planting at Torridge Forest in Devon exhibited high survival and trees had reached an average dbh of 35.7 cm and height of 28 m, 26 years after planting. In the Republic of Ireland, E. nitens is only planted within 30 km of the coast, reducing risk of frost damage (Leslie 2013), which would seem prudent in the UK also.

Eucalyptus pauciflora

A species of eucalypt known to have exceptional cold-tolerance is the snow gum (Eucalyptus pauciflora). This exhibits considerable variation, with three subspecies being recognised; E. pauciflora ssp. debeuzevillei, E. pauciflora ssp niphophila and E. pauciflora ssp pauciflora. At three trials in southern England, individual snow gums from a wide range of origins were productive and are healthy after nearly 30 years. However the growth rate is too slow to make snow gums a viable source of industrial biomass.

Identification of superior origins of snow gums was confounded by patchy survival at the trials, due to rabbit damage at Chiddingfold and windthrow at Torridge in conjunction with self thinning at all three trials. An early assessment at one year old of Torridge and Thetford yielded different results, with E. pauciflora ssp pauciflora from Currango Plains being identified as performing the best in terms of growth and survival (Evans 1986). However at the latest assessment the origins that exhibited a reasonable balance between growth and survival were E. pauciflora origins, particularly of ssp debeuzevillei but also of ssp niphophila from high altitudes (c 1700 m) at Mount Ginini. One origin showed superior survival across the three trials was E. pauciflora ssp niphophila collected at 1830 m altitude from Mount Bogong in Victoria, but rate of growth was relatively poor. While snow gums were more productive than native or naturalised broadleaves, over longer rotations they produced less biomass than some conifer species. Whether yields would be improved if managed as coppice over short rotations is not known, but it is likely, as advocated by Evans (1986) that this species should only be considered for ornamental purposes.

Superior origins identified in this study and in previous studies for the species at the trials assessed in this study are described in Table 6.1.

Other species with potential

There are a number of eucalypts species that were not assessed in the fieldwork for this study but have been identified as having potential in other studies or through more informal observation. E. urnigera, a close relative of E. gunnii may have some potential as it is relatively cold hardy, the foliage is less palatable, but growth rates tend to be lower. The species is being grown in small mixed plantings in Ireland (Leslie 2013) and is considered to have potential for production forestry in that country (Neilan and Thompson 2008).

E. glaucescens, a close relative of E. gunnii is of interest as being relatively fast growing, being unpalatable and having a cold tolerance intermediate between E. gunnii and E. nitens .However, one year results from four Forestry Commission trials showed only one origin, from Guthega, New South Wales to have reasonable cold-tolerance (Evans 1986). The limitations of its cold tolerance were also demonstrated in the extreme winter of 2009/2010; this species survived in the trials in southern England, but was killed in those further north (Harrison 2011). A planting by the Forestry Commission in June 2010 at Thetford, was not affected by the extremely cold winter of 2010/2011 (Primabio no date a).

E. rodwayi, an endemic to Tasmania and found on cold sites prone to waterlogging has been planted as a potential biomass species in Ireland (Leslie 2013). It is considered a species worth testing in the UK (Primabio no date b).

Table 6.1: Summary of the best performing origins of species that may have potential in parts of Great Britain, with notes.

Species	Best performing origin	Source	Notes
E. delegatensis	Var *tasmaniensis* from Ben Lomond, Tasmania	One of the more cold hardy origins in Evans (1986) and confirmed in this study.	Some mainland Australian origins are also hardy (Evans 1986). Recommendation applicable to warm areas of south west Britain. A valuable timber tree (FAO 1979).
E. gunnii	Lake MacKenzie, Tasmania.	One of the most cold hardy origins in Evans (1986) and confirmed Cope, Leslie and Weatherall (2008).	Performs well over a range of locations but variable growth; at 3 years of age trees at Exeter were twice the height of those at Chiddingfold, Thetford, Glenbranter or Wark.
E. nitens	Higher altitude provenances from Victoria.	Evans (1986)	Rapid growth but only to be planted in the least cold and exposed sites. Established as a species for pulp and also for lower grade sawn timber (FAO 1979).
E. pauciflora	Ssp. *debeuzevillei* from Mount Ginini gives a good balance between growth and survival	Ssp *debeuzevillei* in general recognised by Evans (1986) as being particularly cold hardy.	Recommendation applicable to southern parts of Britain. Slow growth makes it more suited as an ornamental.
E. perriniana	Smiggin Holes, New South Wales	This study.	Recommendation applicable to southern parts of Britain. Little planted so a lack of information on timber properties and growth elsewhere.
E. subcrenulata	Mount Cattley, Tasmania	This study and Evans (1986) recommended central or southern Tasmanian origins	Recommendation applicable to warm areas of south west Britain

6.2 To develop volume and biomass functions for E. gunnii and to estimate yields and patterns of growth for E. gunnii.

To develop volume and biomass functions for E. gunnii.

Three approaches have been adopted in Britain to estimating tree volume of eucalypts from measurements of dbh and height. Kerr and Evans' (2011) investigation of eucalypt yields used two methods, the Shell form equation, devised for cold tolerant eucalypts in South America (Purse and Richardson 2001) and the tariff procedure as described in Matthews and Mackie (2006). Tariff relationships have not been determined for eucalypts so the one developed for ash was used. One further method has been used, the AFOCEL volume function and this is particularly appropriate for E. gunnii as it was developed by AFOCEL for E. gunnii and E. gundal hybrids grown in France (AFOCEL 2003a)

As part of this study, a comparison of the precision was made of the Shell and AFOCEL volume functions used to estimate the volume of trees in stands of eucalypts in the UK. As the AFOCEL function was based on E. gunnii or its hybrid, it was likely that it would provide a more accurate prediction of volume and this was the case for all but the smallest trees. In contrast the Shell function was derived from stem form of a wide range of cold-tolerant eucalypts used commercially in South America. It is unlikely that these species would have included E. gunnii. The Shell function was found to consistently underestimate volume (Figure 5.2, Figure 5.3 and Figure 5.4). It is recommended that for estimating volume of trees of greater than 10 cm dbh of E. gunnii in the UK that the AFOCEL function be used.

To estimate yields and patterns of growth for E. gunnii.

In relation to the fourth objective, the main research question was what is the pattern of growth in E. gunnii and at what age is increment likely to be maximised?

Growth curves fitted to historic E. gunnii data estimated standing volume on a 20 year rotation and a stocking of 1,350 stems ha^{-1} at 320 m^3 ha^{-1} (Figure 5.7) or a mean annual increment of 16 m^3 ha^{-1} y^{-1} or 8 t ha^{-1} y^{-1} of dry stem wood. Many of these stands from which these data were recorded have not been intensively managed yet it is instructive to note that early height growth in some stands was at a similar rate to that of intensively managed clonal plantations in France (Figure 5.5). These faster growing stands were at two sites in Nottinghamshire. The rapid growth of the first stand, at Daneshill can be explained by the thorough, intensive silviculture; plastic mulches and fertiliser inputs were used (Forestry Business Services 2004). However the older stand at Thoresby was largely neglected after establishment. These observations suggest that for E. gunnii high growth rates should be possible in the UK, even with unimproved stock and less than ideal silviculture.

However the promising yields from the historic analysis did not take into consideration the considerably higher risk associated with growing E. gunnii on many sites in the UK. Kerr and Evans (2011) in their assessment of historic data from four spacing trials of fast growing hardwoods noted the difficulties in real situations of obtaining consistently high yields across a range of sites from eucalypts, including E. gunnii. This is supported by the highly variable growth rates observed in the historic data for E. gunnii and these data generally represent stands where survival has been reasonable (Table 5.4). The risk of planting eucalypts is discussed further in Section 6.3.

The growth of the trees felled for stem analysis was slower than the trees in the historic data, those at Chiddingfold growing at 7 m^3 ha^{-1} y^{-1} over a period of 28 years. The MAI and CAI for the median tree at Chiddingfold is shown in Figure 5.12. At Glenbranter growth was slower, yielding a MAI of 4.5 m^3 ha^{-1} y^{-1} over 30 years, which increased to 11.4 m^3 ha^{-1} y^{-1} at 43 years of age. There is some evidence that the trees felled at Chiddingfold were not representative of the stand as a whole, being smaller than the mean tree size calculated from TLS plots of the stand. A comparison with the larger historic data set showed that growth at these two locations was relatively poor. These were not the most productive stands in Evans' (1986) analysis of early growth of E. gunni across large plots planted in five locations. Best growth was achieved in the south west of England at Exeter.

At both Chiddingfold and Glenbranter MAI was still increasing when the trees were felled at age 28 years and 43 years respectively. If maximising volume was the sole aim of management, then on similar sites, growing E. gunnii on rotations greater than these ages on would be rational. However, if the time value of money is considered through discounting, then optimum rotations are likely to be considerably shorter. A financial analysis comparing returns from eucalypts with other species is conducted later in Section 6.3.

6.3 To compare growth and other aspects of eucalypts with other promising SRF genera.

This section addresses two of the questions posed by this study

1. Is the production of biomass from eucalypts superior to that of other genera?

2. What are the risks associated with using eucalypts compared with other genera?

For the first research question the first sub-section examines the productivity of eucalypts. This is followed by a comparison of wood production that can be achieved using other genera, after which is a discussion on the relative risk of using eucalypts. Finally a broader discussion compares eucalypts with other tree genera using the ideotype of a SRF tree (Section 1.1).

Is the production of biomass from eucalypts superior to that of other genera?

Estimates for productivity of eucalypts in the UK

Eucalypts are among the most productive trees in the UK and growth from small plots has been estimated to be as high as 30 m^3 ha^{-1} y^{-1} for E. nitens (Purse and Richardson 2001). In Ireland a plantation of E. nitens planted in 1992 at Wexford was felled at 16 years of age to provide material for testing wood properties. The stocking was 740 stems ha^{-1}, tree volume was 0.56 m^3, standing volume was 418 m^3 ha^{-1} and the MAI was 26.1 m^3 ha^{-1} y^{-1} (Hutchinson et al 2011). The historic Forestry Commission data was mined for this study gave a yield of 16 m^3 ha^{-1} y^{-1} for E. gunnii over a twenty year rotation. In general Purse and Richardson (2001) conclude that higher yields of 10-15 odt ha^{-1} y^{-1} over 8 to 10 year rotations are possible from plantations of E. gunnii. This prediction is supported by data from Redmarley in Gloucestershire, where E. gunnii was estimated to have grown at a MAI of 25 m^3 ha^{-1} y^{-1} over a 11 or 12 year rotation (Purse and Richardson 2001). The coppice from this stand was assessed at 10 years of age and the standing volume of mainly E. gunnii with some E. dalrympleana combined was 317 m^3 ha^{-1} or 31.7 m^3 ha^{-1} y^{-1} with 4,746 stems ha^{-1} (McKay 2010).

However, a study analysing historic data from the 1980s highlighted the difficulties in consistently achieving these high levels of productivity. This presented the results of four trials at Bedgebury, Neroche, Ringwood and New Forest that compared growth of eight broadleaved trees, including three eucalypts, all planted at both 1.4 m and 2.8 m spacing. The trial at Bedgebury was abandoned due to poor establishment. At the remaining three, the eucalypts survived well in the first two years at all sites and growth was better than most species. Of the three eucalypts, E. glaucescens consistently exhibited lower survival than E. gunnii or E. archeri. By the age of eight years at Ringwood only E. gunnii showed good growth and the other species had either died or showed poor form (Kerr and Evans 2011).

It was only at the New Forest trial that longer term data were available and where the potential and of fast growth of eucalypts was realised; volume at seven years of age of E. gunnii and E. glaucescens was significantly greater that the other species. Two methods were used to estimate volume, one based on a general formula for eucalypts and the other based on the tariff system. At seven years of age the volume of E. glaucescens was estimated at 78.4 and 89.5 m^3 ha^{-1} respectively, while for E. gunnii it was estimated at 72.7 m^3 ha^{-1} and 57.9 m^3 ha^{-1}. Two spacings were used 2.8 m x 2.8 m and 1.4 m x 1.4 m. The volume at the closer spacing was five times as great for E. gunnii at the close spacing (97 m^3 ha^{-1} compared with 19 m^3 ha^{-1}) and for E. glaucescens twice as great (122 m^3 ha^{-1} compared with 57 m^3 ha^{-1}) (Kerr and Evans 2011). At the wider spacing, E. gunnii at seven years of age was growing at 2.7 m^3 ha^{-1} y^{-1}.

In contrast when E. gunnii and E. nitens that had been damaged or killed by extreme winter cold in the winter of 2010-2011 was harvested at Daneshill in Nottinghamshire at 5 years of old an average of 85 tons were extracted per hectare giving a green weight production of 17 tons ha^{-1} y^{-1} (Wooddisse pers. com.).These data are actual weights harvested from the site, rather than estimates. Despite being located in the cool and dry eastern midlands of England these trees grew very rapidly and this is probably due to the benefits of intensive silviculture.

Further evidence of the considerable variation in growth rate of E. gunnii across Britain was demonstrated by five year results in Evans (1986) across a range of large plots the results of which also showed marked differences in growth, with the height of the best provenance of trees at Exeter (4.7 m) more than being twice as great as those at Glenbranter (1.9 m). Interestingly the height attained was also low in south eastern plantings at Chiddingfold (2.0 m) and at Thetford (2.2 m), possibly due to moisture deficit. The poor growth at Wark (height of 2.6 m), near Kielder is probably due to the cold, exposed conditions at that site. These early data suggest that eucalypt growth is most rapid in the warm but higher rainfall areas of the south west of Great Britain and slowest on colder northern areas of Britain and on drier areas of the south east of England. Kerr's (2011) analysis, based on Kerr and Evans (2011) also showed a wide variation in growth across sites by E. gunnii, with poorest growth being at Neroche near Taunton and best at the New Forest. Growth of E. glaucescens was also most rapid at the New Forest site (Kerr 2011).

Comparison of eucalypt productivity with other genera

There are a number of problems estimating productivity of potential SRF candidate species. Kerr (2011) lists four areas that make estimating yields for SRF imprecise: the shorter rotations, the potential of using 'novel' tree species, the intensive silvicultural approach and the type of sites that would be planted under short rotation forestry. These points will be expanded upon in the following discussion.

The early results of the trial at Newton Rigg, established as part of this study indicated that eucalypts can be more productive than other genera of trees in Britain. By two years of age eucalypts had accumulated two times the stem volume of alder and three times the stem volume of sycamore and ash (Table 4.9). However the one replanting of E. nitens and two of E. gunnii still failed to establish a viable crop on that site, highlighting the risk associated with eucalypts, particularly in northern England due to low temperatures. The lack of knowledge on the limitations of alternative species makes matching their requirements to sites more imprecise. Under intensive silviculture and/or where survival is good, eucalypts can be highly productive (Figure 6.1).

The trial at Newton Rigg also provided some insights into the source of the high potential productivity of eucalypts. Of E. gunnii, alder, ash and sycamore, E. gunnii had accumulated the greatest leaf area after two growing seasons (Table 4.11). While ash had the lowest leaf area of any species, stem volume was not significantly different from sycamore, which had a leaf area about three times as great. Specific leaf area (the ratio of total leaf area and leaf dry weight) was higher in E. gunnii and ash than alder and sycamore. Of the species, E. gunnii was assumed to have the longest growing season (based on its opportunistic growth strategy), while from field measurements alder exhibited the longest growing season, followed by sycamore, with ash having the shortest (Figure 4.3). A growth potential index was created by multiplying an index of length of growing season and leaf area. A non linear regression explained 56% of the variation between individual trees (Figure 4.4), indicating the importance of growing season and leaf area and largely explaining the differences between both species and individual trees.

Kerr (2011) noted that SRF trees can be divided into two broad categories; the first being highly productive and comprising Eucalyptus and Nothofagus and the second being less productive and being made up of other broadleaved genera. Even for species that are widely planted in Britain there are difficulties obtaining definitive growth rates for short rotations. Yield models have been developed for commercial stands but only provide yield estimates that begin at 10 to 25 years depending on Yield Class and species and broadleaved trees are poorly represented compared with conifers (Hamilton and Christie 1971).

Figure 6.1 shows adjacent stands of *E. nitens* and sitka spruce in Cappoquin in County Waterford in Ireland in 2012, the eucalypt being planted in 1992 and the spruce in 1993.

Figure 6.1: P1993 *E. nitens* (left) and P1992 sitka spruce (right) at Cappoquin, County Waterford, Ireland in 2012.

The range of Yield Class (YC) or maximum MAI under conventional forestry rotations of trees identified by Hardcastle (2006) as being suitable for SRF are presented in Table 6.2. These species generally exhibit a peak in MAI at a relatively young age. The most potentially productive genus other than the eucalypts is Nothofagus. Yield models have been developed for Nothofagus in Britain for YC of between 10 to 18 (Tuley 1980). If the mid YC of 14 is examined, Nothofagus MAI peaks at 14.0 $m^3 ha^{-1} y^{-1}$ at 29 years of age (Tuley 1980).

While Kerr (2011) assigned eucalypts and Nothofagus to the fast growing group of SRF species it may be that certain clones of poplar also should be included. Poplars have been used in short rotation coppice due to their rapid early growth (Mitchell, Ford-Robertson and Waters 1993). Work undertaken by Harrison (2009) in Scotland has demonstrated the fast growth of aspen (Populus tremula) and also particularly hybrid aspen (Populus x wettsteinii), while for poplar clones, an average height of 11.8 m and dbh of 22.3 cm was achieved at 12 years of age. The hybrid aspen exhibited more rapid growth with a height of 15.4 m and dbh of 23.2 cm at the same age. A study of clones, including hybrid aspen, across a range of spacings and sites in Sweden showed that high productivity was possible using poplar for SRF. At higher stockings of 2500 stems ha^{-1}, hybrid aspen attained a MAI of 31 $m^3 ha^{-1} y^{-1}$ at age 16 years and poplar a MAI of 9 $m^3 ha^{-1} y^{-1}$ at 9 years old (Christerson 2010).

For sycamore, ash and birch only a generalised yield model exists for the UK that predicts volume growth and this is the one that it is also recommended to be used for alder (Hamilton and Christie 1971). A review of silviculture of alder showed that CAI peaks at 20 years and MAI at between 30 and 50 years (Claessens et al 2010). Sycamore also exhibits an early peak in CAI and MAI and it is described as growing more rapidly than beech up to an age of around 40 years and also that it is a species that responds very well to thinning. It is also noted as being more productive than ash even on the best sites (Hein et al 2008). Ash growth in Germany was described in Dobrowolska et al (2011) and MAI of between 6.2 to 8.6 $m^3 ha^{-1} y^{-1}$ at 60 and 50 years respectively. For birch, the MAI varies from 4 to 10 $m^3 ha^{-1} y^{-1}$ and in most European countries growth is slower than sycamore or ash (Hynenen et al 2009). The mean and range of Yield Class and biomass productivity for the SRF species recommended in Hardcastle (2006) are presented in Table 6.2.

An attempt was made to estimate biomass yields of potential SRF species by Kerr (2011) and these are presented in Table 6.2. In predicting productivity Kerr (2011) made certain assumptions. The first relates to the yield models, with an assumption that with modern silviculture the same yields could be achieved in 75% of the rotation. A second assumption for ash, sycamore and birch was that it was established at a density of 4,444 stems ha^{-1}. Volume yield was then converted to biomass by using specific gravity. As identified by Kerr (2011), the eucalypts and Nothofagus are a more productive grouping of species than the others, with Nothofagus being potentially the most productive of those examined. The low biomass productivity of poplar is partly explained by a lower wood density than other SRF species (Table 6.2).

Table 6.2: The mean and range of Yield Class and biomass productivity for the SRF species recommended in Hardcastle (2006).

Species	Mean YC[a] or MMAI[b] and range	Height in m at age 10 for mean YC and the range	Biomass productivity odt^{-1} ha^{-1} y^{-1}
Eucalyptus nitens	26 to 30[7]	N/A	N/A
Eucalypts gunnii	16[6]	N/A	1.5 to 8.2[5]
Nothofagus	14 (10 to 18)[3]	9.2 (6.8 to 10.8)[1]	3.0 to 10.5[5]
Poplar	9 (4 to 14)[1]	12.7 (8.1 to 16.0)[1]	4.2[5]
Sycamore	8 (4 to12)[1]	6.8 (4.1 to 8.9)[1]	0.6 to 5.7[5]
Alder	4.5 to 14.6[2]	N/A	0.9 to 4.8 (red alder) [5]
Birch	4 to10[4]	N/A	0.5 to 5.7[5]
Ash	6 (2 to 10)[1]	6.8 (4.1 to 8.9)[1]	0.5 to 4.7[5]

[1]Hamilton and Christie (1971), [2]Claessens et al (2010), [3] Tuley (1980), [4] Hynenen et al (2009), [5] Kerr (2011) Table 16, [6]Average for 20 year rotation from historic FC data, [7]O'Reilly, Tobin and Farrelly (2014).

What are the risks associated with using eucalypts compared with other genera?

The risk faced by a tree species comprises two elements; (1) the probabilities of a hazard and (2) the vulnerability of a tree species to that hazard (Petr et al 2014). Predictions of future impacts on tree species are imprecise because of limited knowledge about the level of climate change and tree species responses to that change (Petr et al 2014). However it is clear that the general level of risk to production forestry in Europe and the UK is increasing due to the hazards arising from climate change and the introduction of new pests and pathogens. Predictive models of the effects of climate change on the forest resource in Europe show a considerable reduction in their productive potential and economic value across a range of climatic scenarios. Large areas dominated by softwoods, such as Norway spruce (Picea abies) are likely to be replaced by less productive broadleaves such as oak (Quercus spp.). However a genus that may benefit from these climatic changes is Eucalyptus, with predictions being of an expansion in the areas of suitable sites in the Mediterranean areas of Europe (Hanewinkel et al 2013).

In the UK there are also likely to be major shifts in the productive range of tree species. The 2009 UK Climate Projections simulations provided for the first time probabilities for changes in temperature and rainfall at different levels of greenhouse gas emissions. This has allowed modelling of changes in moisture deficit, which coupled with curves predicting vulnerability to drought enabled a prediction of impacts of future climates on Sitka spruce, Scots pine (Pinus sylvestris) and penduncculate oak (Quercus petraea) (Petr et al 2014) across three IPCC greenhouse gas scenarios (B1 = clean technologies, A1B=balanced, A1F1=fossil fuel intensive). In general the study showed a high probability of a reduction in the productivity of the three species, with up to a 94% reduction in yield class in the lowlands and 64% reduction in the uplands by the 2080s. The greatest impact will be in the south east of Britain (Petr et al 2014).

A further hazard to the forests of the UK is the increase in damage from existing pests and diseases and the introduction of new ones. This has been described briefly in Section 1.2 and several of the damaging organisms attack potential SRF species and is discussed in more detail later in this section.

For comparison, the risk associated with potential SRF species has been divided into two main areas, each of which was divided into three. The first main area of risk was the hazards impacting the tree, which included abiotic factors, biotic factors and also the market risks. The second main area of risk is the hazards arising from the tree which has been divided into impacts on biodiversity, invasiveness and potential of hybridisation, the categories being based on an analysis of ecological risk of introduced trees by Felton et al (2013) and also a further one on impacts on abiotic factors in the environment.

Hazards to the tree

Abiotic hazards

Climate change will impact all the potential SRF species in Hardcastle's (2006) list. In general for all species, under high and low emissions scenarios there will be a considerable reduction in the productivity on sites in south east of England by 2080s (Petr et al 2014). In a review of the impact of climate change on eucalypt plantations in general, Booth (2013) assessed their vulnerability as being moderate. However he also noted that the short rotations, compared with conventional forest rotations offered greater opportunities to change genotypes and silvicultural practices over time which reduced risk. However in terms of risk from exceptionally cold periods, of the species listed by Hardcastle (2006), Eucalyptus and Nothofagus are particularly vulnerable.

In a study Murray, Cannell and Shepard (1986) found Nothofagus alpina to be hardier than Nothofagus obliqua. For both species, hardening and dehardening follows variations in temperature making them susceptible to unseasonal cold damage (Deans, Billington and Harvey 1992). The most hardy provenances of N. alpina were from Neuquen in Argentina, and from mature trees of Malleco (Chile) that were growing in Britain. Deans, Billington and Harvey (1992) found significant differences between two provenances of N alpina, but only one tree was significantly different in cold hardiness within provenances. Murray, Cannell and Shepard (1986) noted that there is a high risk of Nothofagus being damaged at least once during a conventional rotation except in mildest coastal areas of Britain where temperatures of -14^{o}C or lower are experienced only once in 50 years. However if the hardiest individuals are selected that are 3 to 6^{o}C more hardy than the population means then they may be suitable for planting in most lowland parts of the UK (Murray, Cannell and Sheppard 1986). A consequence of periods of cold winter temperatures is damage to Nothofagus through stem cankers. These are caused by death of cambium and in severe cases the tree can be girdled. Rapidly growing trees in locations subject to rapidly fluctuating temperatures appear most at risk. However, it is only in the worst situation that the stands as a whole are severely affected (Tuley 1980).

Eucalypts are also at the margins of their climatic limits in most of the UK and severe winters cause extreme damage in many areas where eucalypts have been planted. Over the period of this study there were two extreme winters, that of 2009-2010 and the following winter of 2010-2011. The widespread stem mortality caused during these winters to E. gunnii and E. nitens at Daneshill, Nottinghamshire and across a range of sites planted in England (Harrison 2009) confirms the high risk associated with eucalypts. However, 2009-2010 was the coldest winter in thirty years and in some part of England in 100 years (Prior and Kendon 2011) and 2010-2011 was only a little less severe (Met Office 2011). However, while the stems and foliage of E. gunnii were killed at Daneshill, many of the trees later produced coppice shoots. To lower the risk of planting eucalypts in Britain the focus should be on species that coppice, rather than the few species like E. nitens that do not have this capability (Boyer no date).

At a trial at Newton Rigg in Cumbria, cold damage to E. nitens and E. gunnii, planted the previous spring was greatest to tissues of the smallest trees (Table 4.13). This reinforces the importance of obtaining rapid early growth and a tree of 1 to 1.5m in height before the first winter. Large trees have greater sap reserves, the vulnerable foliage is higher above the ground and above radiation frosts (Davidson and Reid 1987) and they exhibit greater physiological maturity, all contributing to greater resistance to cold damage. However, relative height growth was greatest in the smallest transplants (Table 4.6) and it is recommended that a transplant of between 20-30cm in size be used and adopting intensive silvicultural practices to ensure a 1.5m tall tree is achieved before winter. Barrnard (1968) recommended using a transplant of at least 15cm in height.

The approach suggested by Murray, Cannell and Sheppard (1986) of excluding areas where minimum temperatures of -14^{o}C occur more than once every 50 years may provide some measure of the suitability of different areas across the UK for planting Nothofagus and eucalypts. This was proposed in a presentation by Ray (2005). A more sophisticated method has been used by FCBA (2010) in France to identify areas where E. gunnii and E. gundal are most productive. As a measure of suitability of climate, the mean number of days per year where minimum temperature dropped to below -12^{o}C was used. A similar measure could be incorporated into the Ecological Site Classification to assist identification of areas suited to less frost-hardy tree species.

To examine whether the higher yields from eucalypts offset the greater risk of damage from extreme cold periods, a financial analysis was undertaken, making certain assumptions on yield and costs (Appendix 9). The following scenarios were investigated:

1. All species grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. No damaging incidents.

2. E. gunnii grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. E. gunnii frosted and stems killed at 10 years but resprouted.

3. E. gunnii grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. E. gunnii frosted and killed completely at 10 years requiring replanting.

4. E. gunnii grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. E. gunnii frosted and stems killed at 50 years but resprouted.

5. E. gunnii grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. E. gunnii frosted and killed completely at 50 years requiring replanting.

Net discounted revenue was calculated using a discount rate of 5% for the calculation of net discounted revenue. Internal rate of return was also calculated using the IRR function in Excel. A summary of results is shown in Table 6.3 and more detail in Appendix 9. At a 5% discount rate most of the E. gunnii scenarios provide a positive financial return, with the exception being a stand frosted at year 10 and replanted (Scenario 3). Under the scenarios chosen E. gunnii provided better financial returns than alder and poplar unless replanting was required at age 10 years.

Table 6.3: Net discounted revenue (at 5% discount rate) and internal rate of return for different SRF scenarios.

Description	**NDR @ 5% (£)**	**IRR (£)**
1. Alder grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. No damaging incidents	-1609.15	2.5%
1. Poplar grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. No damaging incidents	-4.40	5.2%
1. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. No damaging incidents	1030.51	6.3%
2. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and stems killed at 10 years but resprouted.	883.32	6.2%
3. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and killed completely at 10 years requiring replanting.	-403.99	4.5%
4. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and stems killed at 50 years but resprouted.	904.18	6.4%
5. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and killed completely at 50 years requiring replanting.	420.01	6.3%

Biotic hazards

The risk of damage to trees from biotic agents is predicted to increase (Sturrock et al 2011, Logan, Régnière and. Powell 2003). There are damaging pests and pathogens associated with all of the SRF species on Hardcastle's (2006) list. An informative resource for appraising the risk from particular insect pests and pathogens is the online UK Plant Health Risk Register. This gives a scoring for likelihood, spread, impact, value at risk, likelihood x impact and an overall risk rating for each particular insect pest or pathogen. However the register does not provide an overall risk rating for a tree species. A framework for assessing the impact and risk of pests and pathogens on commonly planted trees established under the Woodland Carbon Code scheme was developed by Davies, Patenaude and Snowdon (draft article). However it failed to recognise the importance of mammalian pests as damaging agents of some species. For example, sycamore was given a lower risk rating than birch, yet sycamore cannot currently be grown as a commercial crop in many areas of Britain due to damage by grey squirrel (Sciurus carolinensis) (Savill 2013). As such there is at this time no practical formal rating of risks to SRF tree species from biotic agents. However potential SRF tree species can be broadly divided into four groups in terms of risk from pests and pathogens. The first group includes ash and sycamore, the second alder, poplar and Nothofagus, the third comprises birch and the fourth comprises the eucalypts.

The first group are those tree species currently at high risk from damage with ash no longer being planted due to the predicted damage from ash dieback (Woodward and Boa 2013). Furthermore, an additional risk is that from Emerald ash borer, which is now present in Russia (Straw et al 2013). The other species in this group is sycamore as the severe damage caused by grey squirrel makes planting this species uneconomic in areas where high squirrel populations are present (Savill 2013). In terms of pathogens, Webber et al (2011) note that and Phythophthora spp and Verticilium wilt can be damaging in nurseries or newly planted stock. A greater concern is Cryptostroma corticale that can remain dormant in the tree until it becomes stressed by prolonged dry conditions. The pathogen then causes an ailment known as sooty bark disease, which results in crown dieback and can cause death of the tree.

The second group comprises tree species where there are identified and potentially serious pests or pathogens that are already established in Britain. This group includes alder and Nothofagus which are at threat of damage from Phytophthora alni (Gibbs, Lipscombe and Peace 1999) and Phytophthora pseudosyringae (Scanu, Jones and Webber 2012) respectively. It also includes poplars, plantations of which have been severely damaged by rusts (Melampsora spp) in the UK (Forestry Commission 2005).

Damage by P. alni was first noted in Britain 1993 primarily infecting and killing the native alder, but also grey alder (A. incana) and Italian alder (Alnus cordata) (Gibbs, Liscombe and Peace 1999). Symptoms include an abnormally sparse crown in summer and tarry lesions on the stem (Webber, Gibbs and Hendry 2004). In France and Germany damage has been considerable in some localities (Webber, Gibbs and Hendry 2004) although as a water borne disease in Britain it has mostly affected riparian trees. Survey data from rivers in southern England and Wales collected in 2003 showed 15% of such trees being infected by this pathogen (Webber, Gibbs and Hendry 2004). By 2011, up to 20% of riparian alder exhibited dieback or death (Webber et al 2011). Webber, Gibbs and Hendry (2004) warn against planting alder on riverine sites and sites which are prone to flooding. This recommendation is supported by recent research that shows that flooding also increases damage in infected trees, probably due to the trees being more stressed (Strnadová et al 2010). Other recent work (Černý, Filipova and Strnadová 2012) demonstrates that cold temperatures will kill the pathogen and suggests with predicted increases in winter temperatures due to climate change, damage from this pathogen may increase.

Infection by P. pseudosyringae of Nothofagus was first noted in 2009 in a stand of N. obliqua in Cornwall, where in four plots between 50% and 72% of trees had become infected. Symptoms include bleeding lesions on the trunk and dying foliage and crown dieback (Scanu, Jones and Webber 2012). The susceptibility of Nothofagus to this disease prompted Scanu, Jones and Webber (2012 p27) to comment 'A consequence of this damaging new disease is that future use of N. obliqua and N. alpina in UK forestry as suitable species for climate change adaptation strategies could be limited'.

Poplars are susceptible to attack by rusts (Melampsora spp). Rusts cause premature leaf fall and can also disrupt hardening in some hosts and other damage can include a reduction in growth, shoot die back and when severe, tree death. Developing varieties of poplar resistant to rusts and also to the highly damaging Xanthomonas populi that causes stem cankers in is the main strategy to produce disease free stands. In the past the Forestry Commission published a list of resistant varieties (Forestry Commission 2005) and a mix of resistant clones should be planted so as to reduce risk further (Lonsdale and Tabbush 2002). While it was thought that poplar grown in the densely stocked SRC is more susceptible to rusts, since the 1990s there has been an increase in damage of stands of trees (Lonsdale and Tabbush 2002). By 1999 there were no longer any fully rust resistant varieties (Tabbush and Lonsdale 1999), which presents a serious limitation to growing productive poplar plantations. This increase in risk was demonstrated by a devastating outbreak in 2005 of what is thought to have been Melampsora larici-populina in single stem plantations at wider spacing (Forestry Commission 2005).

The third group comprises birch, which is currently relatively free of major damaging biotic agents, although it is susceptible to attack by Armillaria (Webber et al 2011). Furthermore, there have been problems in crown dieback in recent plantings of birch in Scotland due to three pathogens; Anisogramma virgultorum, Marssonina betulae and Discula betulina (Green 2005). However it is the threat from a particular pest currently absent from the UK that is probably the greatest threat to birch. This is the bronze birch borer (Agrilus anxius), which if introduced would have a devastating impact across Europe (Nielsen, Mullenberg and Herms 2011). Birch and downy birch (Betula pubescens) are highly susceptible. Within 8 years of planting in a trial in the USA, all individuals of these birch species had been killed by the borer (Nielsen, Mullenberg and Herms 2011). A simulation showed that the probability of detection of bronze birch borer in wood chips was extremely low using the current protocols in Europe (Okland, Haack and Wilhelmsen 2012). This finding however contrasts with a risk assessment that suggests that with current measures the likelihood of bronze birch borer arriving in Britain is relatively low (European and Mediterranean Plant Protection Organisation 2011).

The final group comprises the eucalypts. These are probably the lowest risk in terms of damage from pests and diseases as very few native pests of eucalypts have been introduced to plantations outside Australia (Fanning and Barrs 2013). While there are damaging pathogens in eucalypt plantations overseas, the eucalypts identified as being suited to SRF in Britain are not those most susceptible to Phytophthora spp or to foliar pathogens (Webber et al 2011). There are no records of major pest outbreaks in the UK, however there have been outbreaks of pests in Ireland, which have damaged eucalypts grown for foliage for floristry. In the late 1990s a psyllid, Ctenarytaina eucalypti was introduced to Ireland (Chauzat, Purves and Dunn 2001). Chemical control was not particularly effective and so a parasitic wasp, Psyllaephagus pilosus was introduced and this effectively controlled the psyllid (Chauzat, Purves and Dunn 2011). In 2007 a leaf beetle, Paropsisterna selmani caused severe defoliation in multi species plantings of eucalypts (Fanning and Barrs 2013, Horgan 2012). Fanning and Barrs (2013) describe the beetle as being a serious threat to eucalypts in Ireland, the UK and more widely in Europe as the adults are strong fliers, capable of surviving long periods without food and are able to tenaciously cling to various materials.

Market risks

The more specialised the products or the smaller the range of products derived from a tree species, the higher the risk of financial loss from changes in markets. Most of the tree species listed in Hardcastle (2006) as having potential for SRF produce wood that has uses other than biomass. A constraint to marketing the wood of many of the species is however the current limited volumes of wood available.

Nothofagus, alder, poplar and birch currently have limited markets. Nothofagus wood provides a flexible resource and in Chile is used for a variety of purposes including furniture, flooring and veneer. It is noted being structurally strong and as being highly resistant to decay. Wood grown in the UK has been found to dry slowly, with little degrade and has been used for turnery and pulp (Tuley 1980). It is also suited to flooring (Aaron and Davies 1990). However the small quantities normally on the market may make it initially difficult to sell in the UK (Tuley 1980) but in countries where there are larger quantities available it is widely accepted on timber markets (Savill 2013). Alder is rarely found in large dimensions and while not durable, both heartwood and sapwood readily accept preservatives. It is used for plywood on an industrial scale in Eastern Europe (Fennessy 2004). Poplar wood is low in strength in every property except stiffness. Many of its traditional uses; match sticks and fruit crates have been lost but it is still a versatile wood for indoor uses only, as it is not durable and does not readily accept preservatives. When ignited it tends to smoulder rather than produce flames, making it suited to applications where flame retardation is useful (Aaron and Richards 1990). The small dimensions and lack of straight logs has constrained the use of the use of birch wood in the UK. It is however one of the strongest hardwoods and can be used for a wide variety of applications. Although not durable, it will take preservatives (Aaron and Richards 1990).

The wood of sycamore and ash has more established markets in the UK. Sycamore produces a wood that is as strong as oak, but with a uniform light colour and which can be worked into a fine finish. This makes it suitable for a wide range of uses. Its pale colour and lack of odour make it popular for making items in contact with food (Aaron and Richards 1990). Ash is one of the strongest domestically grown hardwoods and so is often used for tool handles and in the past for carriages and 'woody' estate cars (Aaron and Richards 1990). The wood of Eucalyptus nitens is used as a source of pulp, although it is poor quality and not suitable for many eucalypt market kraft uses (Kibblethwaite, Johnson and Shelbourne 2001) and can be used as for sawn timber but there are difficulties in preventing drying defects such as splitting and warping (Hamilton et al 2009). E. gunnii is grown in France for pulp but the wood is not ideal. This is because it has a high lignin content which reduces pulp yield. However, in mitigation the pulp refines easily and the traction and burst properties of the fibre are by far better than those obtained for E. globulus (da Silva Perez et al 2011). As a fuelwood E. gunnii has a high moisture content and is not easily dried (Leslie 2013), however its high lignin content compared with E. globulus may be beneficial as a fuel (da Silva Perez et al 2011). The highest market risks therefore exist from growing eucalypts, as the wood has limited applications other than for biomass. There is also currently a very limited extent of productive plantations.

Hazards from the tree

Under the Great Britain Non-native Species Risk assessments (GB Non Native Species Secretariat no date a, GB Non Native Species Secretariat no date b), reviews were conducted of the risk associated with E. gunnii and E. nitens. The conclusion of the analysis for both species was that they were both in the upper level of the 'low' risk category in terms of environmental impact. Formal risk assessments had not been undertaken for the other exotic species on Hardcastle's (2006) list.

Impacts on biodiversity

Many of the native and naturalised and native SRF species are beneficial to biodiversity. The online Database of Insects and their Food Plants (Biologiical Recording Centre undated) provided lists of the phytophagous insect species associated with each of the tree species in the UK and Harding and Rose (1986) of lichens. These are described below in Table 6.4. The high levels of lichens supported by sycamore, a naturalised tree is notable. However this diversity is associated with older trees and stands of SRF are likely to support lower levels of biodiversity, particularly of lichens.

Table 6.4: Phytophagous insects and lichens associated with SRF tree species.

Species	**Number of insect species[1]**	**Number of lichen species**
Eucalyptus nitens	1	-
Eucalypts gunnii	1	-
Nothofagus oblique	31	-
Nothofagus Antarctica	22	-
Poplar (*P. trichocarpa* X *deltoides*)	1	-
Polar (aspen)	223	>130[3]
Sycamore	119	194[2]
Alder	190	116[2]
Birch	192	134[2]
Ash	101	265[2]

[1] Biologiical Recording Centre (undated), [2]Harding and Rose (1986), [3]Street and Street (2001), from a survey in Strathspey, Scotland.

Of the exotic trees, Nothofagus provides a host to a considerable range of Lepidoptera, many of which are generalists but some of which are associated with oak and beech. This on occasion makes them vulnerable to defoliation when planted near to beech or oak (Welsh and Greatorex-Davies 1993). There are limited studies on the effects of eucalypts on flora and fauna in the UK. A survey of fungi in stands of E. gunnii and E. nitens (Pennington, Bidartondo and Barsoum 2011) showed that most of the mycorrhizal fungi were associated with eucalyptus and originated from Australia, with a limited number of native British species. However a later survey at Daneshill identified a number of rare fungi species, including three species representing three new genera to the UK (Hobart 2012). A study of earthworms under SRF and in comparison with pasture provided useful results (Rajapaksha et al 2013). Their conclusion was that if development or maintenance of earthworm populations was an aim, that SRF should focus on native species, such as alder, birch and ash, but also E. nitens, which also supported dense populations of earthworms. Results for E. gunnii were also encouraging, on a loamy arable site, earthworm population density was maintained and on a reclaimed site, densities were increased, compared to unplanted areas.

Invasiveness

The risk of invasiveness of E. gunnii and E. nitens is low. For both species, seed germination can be poor and the seedlings are susceptible to frost damage and for E. gunnii they are also palatable. Furthermore for both species, the small seed size means that seedlings have few reserves and are vulnerable to competition from other plants. (GB Non Native Species Secretariat no date a, GB Non Native Species Secretariat no date b). There are few sites where natural regeneration of E. gunnii has been observed (GB Non Native Species Secretariat no date a) and none where E. nitens has been noted (GB Non Native Species Secretariat no date b). In general, Booth (2013) notes that the risk of invasiveness of eucalypts in frost prone areas of the world is low.

The other SRF species where there are concerns about being ecologically damaging (Peterken 2001) and in particular being invasive is sycamore (Binggeli 1992). It is classified as an invasive species in several Scandinavian countries (Felton et al 2013). In Sweden sycamore has established itself in disturbed and undisturbed forest (Felton et al 2013). However the rate of invasion in the UK tends to be slow due to its sensitivity to grazing and competition from ground vegetation and also a requirement for disturbance in closed woodland (Binggeli 1992). Peterken (2001) concludes that while it can dominate the dynamics of native woods and suppress ground vegetation it is unlikely to dominate native woods completely and furthermore offers some useful biodiversity benefits.

Potential for hybridisation

There may be a general concern about gene flow from exotic provenances impacting on the genes of locally distinct populations of native trees. Of the SRF species selected by Hardcastle (2006) there is greatest potential for hybridisation to occur between SRF poplar clones and native poplar species (Roe et al 2014). This is a concern where there are locally distinct populations, such as found in aspen and black poplar (Populus nigra) in Britain. There is a low probability of gene flow between clones and local populations of aspen because flowering is rare in the UK (Worrell et al 1999). Black poplar in Britain belongs to the endangered subspecies betulifolia, but the likelihood of hybridisation is low due to the species' limited distribution and that there are as few as 600 female trees only in the UK (Savill 2013).

Impacts on the abiotic environment

There have been concerns about the environmental impacts arising from planting eucalypts, but that such impacts related to specific situations and could not be generalised (Poore and Fries 1985). In a review of predicted impacts of SRF on water quality and quantity no specific problems were associated specifically with eucalypts, rather with intensively grown plantations (Nisbet, Thomas and Shah 2011). Over 1000 ha of plantations of species similar to those that can be planted in the UK have been established in France and water use was a concern (AFOCEL 2004). However for the biomass produced water use is similar to that of other trees (Stanturf et al 2013). Indeed, Savill (2013) notes that many fast growing broadleaves have the capacity to transpire large quantities of water, including ash, alder, poplar and willows.

Assessment of SRF species against the SRF ideotype

The following general criteria define part of the SRF ideotype that was introduced in Sections 1.1 and were:

- Fast growth and high biomass yield (Guidi et al 2013), with MAI peaking early.
- Resistant to pests and diseases and extremes in climate, such as cold and drought.
- Reproductive or other characteristics that limit the likelihood of invasiveness (Gordon et al 2011).
- Low negative impacts on the environment, such as soil nutrients and moisture (Ranney and Mann 1994).

There remain however some general physiological, morphological and wood characteristics that are attractive in a SRF species:

- The ability to coppice (Dickman 2006, Hinchee et al 2009, Guidi et al 2013), avoiding the costs of planting and also enhancing growth rates in the second and subsequent rotations.
- Producing straight stems; lowering harvesting, handling and transportation costs (Walker et al 2013)
- High density wood (Ramsay 2004),
- Wood with a low moisture content (Ramsay 2004),
- Wood with suitable chemical characteristics for combustion (Ramsay 2004),

Table 6.5 describes the recommended SRF species in Hardcastle (2006) in relation to these wood and regeneration characteristics.

Table 6.5: Specific gravity, green moisture content and coppicing or suckering ability of SRF tree species.

Species	Specific gravity	Green Moisture content *	Coppicing/ suckering ability
Eucalyptus nitens	0.45[2]	-	Poor[15]
Eucalypts gunnii	0.50[4]	-	Good[4]
Nothofagus	0.6[5], 0.45 to 0.53[6]	-	Good[16]
Poplar	0.36[7], 0.335[8] (aspen 0.48[9])	64%[10], 49-56%[13]	Good[17], but variable[18] aspen suckers[18]
Sycamore	0.63[1] (MC 12-17%)	41%[10]	Good[16]
Alder	0.54[3] (MC 12%), 0.43-0.49[12]	-	Good[16]
Birch	0.662[11] 0.53[14]	43%[10]	Moderate[14]
Ash	0.674[11]	32%[10]	Good[16]

[1]Hein et al (2008), [2]Kibblewhite et al (2000), [3]Claessens et al (2010), [4]AFOCEL(2004), [5] Tuley (1980), [6]USDA (no date), [7]Kerr (2011) Table 16, [8]Christerson (2010), [9]Harrison (2009), [10]Forestry Commission (2011), [11]Solid Fuel association no date. [12]Milch et al (2015). [13]Tharakan et al (2003), [14]Cameron (1996), [15]Sims et al (1999), [16]Evans (1984), [17]Mitchell, Ford-Robinson and Waters (1993), [18] Mc Carthy, Ekö and Rytter (2014), [19]Eadha Enterprises (2012). *Wet weight basis

Ability to coppice or sucker

The SRF species on Hardcastle's (2006) list all coppice or sucker, with the exception of E. nitens. A study in New Zealand showed that E. nitens produced few coppice shoots after cutting and after three rotations the stools were dead. The same study found that E. urnigera and E. rodwayi consistently produced vigorous shoots over five coppice cycles (Sims et al 1999) and Eucalyptus gunnii is also known to coppice vigorously (AFOCEL 2004). Nothofagus is recommended for producing firewood production through coppice by Evans (1984).

Ash, alder and sycamore yield productive coppice (Evans 1984). Birch also coppices, but more poorly than downy birch (Betula pubescens). As such, Cameron (1996) does not recommend coppice as a way of regenerating stands for timber. Perala and Alm (1990) note that poor stocking seems to be a consequence of regenerating birch stands by coppice. Poplars are known to regenerate vegetatively; hybrid poplars are employed in short rotation forestry and coppice vigorously over multiple rotations (Mitchell, Ford-Robertson and Waters 1993). Aspen also regenerates effectively after harvesting with an average of two shoots developing from the rootstock and three from suckers (Eadha Enterprises 2012).

Specific gravity

Dense wood is an attractive trait in trees used as fuel. Specific gravity was measured for the two year old saplings at the trial at Newton Rigg (Table 4.10). The least dense wood was alder, with E. gunnii and ash having the same specific gravity and sycamore being lighter. These findings are similar to those of research on mature trees (Table 6.5), where alder and poplar have a low wood density, the eucalypts and Nothofagus have moderately dense wood and the wood of sycamore, ash and birch is higher density.

Moisture content

Moisture content of wood was measured for saplings at the Newton Rigg trial at 2 years old and so represented small woody material. The ranking of high to low green weight moisture content was alder (59%), sycamore (56%), E. gunnii (55%) and ash (48%). Moisture content for larger material is shown in Table 6.5 and in general moisture contents are lower, but ash remains the wood with the lowest moisture content. Poplar, which was not planted at Newton Rigg has the highest moisture content of trees where data are shown. Experience in Ireland has shown that drying E. gunnii can be problematic. It was found that the wood only dried rapidly when the bark was removed and this itself was difficult using machinery because of its fibrous nature (Leslie 2013).

Combustion properties

Many of the species in Hardcastle's (2006) list have not been burned for energy on an industrial scale. Some, such as ash are known as producing good domestic fuel wood due to its low moisture content (Table 6.5). In Sweden birch is widely used as a source of domestic heat (Hedberg et al 2002). A study of the effects of torrefaction (a process similar to converting wood to charcoal) on the wood of six tree species, including birch and aspen showed that the wood of the two eucalypt species tested contained much higher levels of chlorine (Keipi et al 2014), which can be corrosive in boilers and pipework in power plants. There are differences in combustion properties between eucalypts; the calorific value of wood from E. gunnii SRC was noted as being less than some other eucalypts (Forrest and Moore 2008).

Stem form

A regular, straight stem enables more efficient handling, storage and processing. Potential SRF species known to exhibit good stem from include E. nitens (Neilan and Thompson 2008), poplars (Savill 2013) and silver birch (Hynynen et al 2010). The stem straightness of Nothofagus alpina is better than N. obliqua, with N. obliqua being similar to beech but N. procera being as good as poplar (Tuley 1980).

Many of the SRF species show a wide variation in stem form between individuals. Ash is sensitive to frost damage and this can result in poor stem form through death of the leader and so frost prone sites should be avoided (Dobrowolska et al 2011). Sycamore shows considerable variation in stem form (Hein et al 2009). Young alder often exhibits a straight stem with a compact pyramidal crown, but stem form becomes more inconsistent as the trees age (Savill 2013). Stem form of E. gunnii is variable and often poor (Primabio no date c, Marriage 1977), but improved material used in France exhibits good stem form (AFOCEL 2007).

Overall strengths and weaknesses of eucalypts as a SRF tree

In summary, eucalypts meet many of the requirements of an ideal biomass tree and compare favourably with other potential SRF species. The strengths of eucalypts in comparison with other SRF trees are:

- Potentially high biomass yields over short rotations;
- That most species that are suitable for British conditions coppice well;
- Relatively dense wood;
- Many species exhibit excellent stem form;
- The low risk of damage from biotic agents.

While the weaknesses are:

- Lack of knowledge to reliably ensure effective matching of species to site;
- Higher risk from extreme cold or unseasonal periods of cold on certain areas than most other SRF trees, except possibly Nothofagus.
- High wood moisture content and some difficulties drying the wood in some species;
- The wood of many cold-tolerant eucalypts is not suited to markets other than biomass.

6.3 Recommendations

The recommendations are divided into two parts, the first relating to those arising from the findings of this study and the second describing future work that should be undertaken.

Recommendations arising from this study

When establishing eucalypts it is recommended that:

Intensive silvicultural techniques be used, that cultivation is practiced and that timely and thorough weed control is undertaken. This will allow good root development, early stand stability and enable the site to be captured rapidly. That for a 15 to 20 year rotation a stocking of 2,500 stems ha^{-1} as practiced at Daneshill Energy Forest (Forestry Business Services 2004) be adopted enabling site capture within 2 to 3 years.

In terms of planting material, it is recommended that a transplant of between 20-30cm be used as a compromise between growth, survival and stability. A further reason for intensive establishment techniques is to ensure a tree of 1.5m height or greater is achieved before the first winter. This will reduce the likelihood of fatal or extreme frost damage by ensuring foliage is sufficiently above ground level;

Until there is a better understanding of cold tolerance of species, the recommendations of Murray, Cannell and Sheppard (1986) for Nothofagus be applied to eucalypts and that areas where minimum temperature of below -14°C are experienced every 50 years are avoided for larger plantings. Furthermore, the constraints suggested by Ray (2005) and incorporated into ESC should be followed as a guide to site suitability.

Stands should be established using the origins identified as combining good survival and growth and on sites similar to those where those origins have been previously planted (Table 6.1). As there are difficulties in obtaining seed of some of these origins, and there is considerable variation within origins, it is recommended that seed be collected from superior individuals at the Forestry Commission trials (See next sub-section).

Recommendations for future work

The main foci for future work are the provision of well-adapted seed and developing a better understanding of matching species to site. To provide a source of well-adapted seed it is recommended that:

Seed collection be undertaken from individuals with good growth and stem form from stands of superior origins. It may be opportune to selectively thin some stands to convert them to seed stands, such as the E. subcrenulata stand at Haldon (Section 3.2).

Kerr and Evans (2011) in their review noted that if biomass production is to be maximised a priority is to identify optimum sites for eucalypts. To better match eucalypts species to site it is recommended that:

Land owners be encouraged to register and provide details of growth and survival of existing stands of eucalypts using the SilviFuture online database (Silvi Future no date). Only E. gunnii and E. nitens are currently supported and they are noted as low priority species. By 27 September 2014 there were only 2 records for E. nitens and one for E. gunnii and the data provided was insufficiently detailed to be useful for assessing the performance of those species on those sites.

Small plantings of those species recommended in section 6.1 be established across a range of altitudes, latitudes and soil types to better define their site requirements. In the southern USA, small plantings have been established of a wide range of origins of eucalypts over a broad range of sites to examine their site tolerances (Stape et al 2012).

In addition to investigating origins and providing a supply of superior seed, Kerr and Evans (2011) suggest more work be undertaken in developing appropriate silvicultural systems directed at biomass production on short rotations. An example given by Kerr and Evans (2011) was adopting high stocking, a systematic thin within the rotation and singling the coppice. They also recommended the use of mixed species stands to reduce risk and to maximise site resource capture.

6.4 Conclusion

There were three main objectives of this study and progress has been made in meeting those objectives:

1. To identify the species and provenances of eucalypts most suitable for biomass production in Great Britain

This study has identified superior origins of E. subcrenulata, E, delegatensis and also E. perriniana that could be planted in warmer parts of the UK. It has also confirmed that E. gunnii is a particularly cold-tolerant species of eucalypt, but that it is susceptible to mammal damage through browsing. Material from Lake MacKenzie or other hardy origins identified in Evans (1986) should be used. While there are origins of E. pauciflora suited to southern parts of England, the slow growth of this species makes it unsuitable for production forestry. This work supports the recommendation by Evans (1986) that is best suited as an ornamental tree. E. nitens, a species of limited cold hardiness but exceptionally rapid growth should only be established on the warmest of sites and using the origins recommended in Evans (1986). In Ireland it is recommended to plant this species only within 30km of the coast to reduce risk of frost damage (Leslie 2013).

2. To develop volume and biomass functions for E. gunnii and to estimate yields and patterns of growth for E. gunnii.

A volume function developed for plantations of E. gunnii and E. X gundal in France provided a precise and accurate estimation of tree stem volume based on measurements of dbh and height. However it is not suited to small trees, those of less than 10cm dbh. A growth curve derived from historic data from a range of sources indicated that a volume of 320 m ha^{-1} can be achieved on a 20 year rotation at a stocking of 1,350 stems ha^{-1}. This corresponds to a MAI of 16 m^3 ha^{-1} y^{-1} or an approximate biomass yield of 8 t ha^{-1} y^{-1}. However yields based on stem analysis of trees from Chiddingfold and Glenbranter were much lower, at 7 m^3 ha^{-1} y^{-1} at 28 years and 11.4 m^3 ha^{-1} y^{-1} at 43 years respectively. Considerable variation in growth of E. gunnii between sites at 5 years of age was noted in Evans (1986) and there is also some indication that the trees, sampled at Chiddingfold were relatively small.

The stem analysis provided some insight into the pattern of growth of E. gunnii. However, all but the dominant trees had been suppressed due to the close initial spacing and lack of thinning. There was a dramatic drop in growth in more recent years as indicated by narrow or missing annual rings. However it would appear that MAI peaks on relatively unproductive sites like Glenbranter at beyond an age of 43 years.

3..To compare growth of eucalypts with other promising SRF genera

The productivity of eucalypts has the potential to be higher than other genera in Britain, except possibly Nothofagus (Table 6.2). However this high productivity is difficult to achieve in a consistent manner and there are many instances of complete failure. Of the eucalypts tested in Britain, it is E. nitens that has the most rapid growth, with productivity up to 30 m^3 ha^{-1} y^{-1} on short rotations (O'Reilly, Tobin and Farrelly 2014), but is not sufficiently hardy for most sites in Britain. In terms of other characteristics attractive to biomass production, eucalypts compare favourably with other genera, having moderately dense wood and mostly good stem form, although a relatively high moisture content and also high chlorine emissions (Keipi et al 2014) when burned are weaknesses.

There is a limited extent of eucalypt planting and this means there is a higher risk of unsuitable sites being selected for planting. Many of the other genera or species identified as being suitable for SRF have been planted more widely and over larger areas. Furthermore, even the most cold-tolerant eucalypts are at their climatic limits in Britain and at risk from extreme cold events. Climate change is predicted to result overall in warmer winters but this positive impact may be mitigated by greater extremes in temperatures, which would include cold events.

The risk of damage from cold can be limited by selecting areas known to have a low probability of cold conditions as suggested by (Murray, Cannell and Sheppard 1986) for Nothofagus and adopted by Ray (2005). At a smaller scale, cold air drainage and frost hollows should be avoided.

Risk of damage to eucalypts from biotic agents is less than most other SRF species or genera. The planting of ash has generally ceased in Britain due to concerns about damage by ash dieback. Both Nothofagus and alder are susceptible to damage by Phythophthora spp and there are many areas where grey squirrel prevents commercial planting of sycamore (Savill 2013). Furthermore, there are now no commercial hybrid poplar clones that are resistant to Melampsora rusts (Tabbush and Lonsdale 2002).

In conclusion, eucalypts have a role in diversifying the range of species planted in production forests in the UK. However, the extent to which they are planted is likely to be limited as many species of cold-tolerant eucalypts are at their climatic limits in Britain. Taking a cautious approach to selecting sites and appropriate silviculture will reduce significantly the risk of failure.

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Appendix 1 Key publications on Eucalyptus in the UK and Ireland since 1950

Table A1.1 Key publications on eucalypts relevant to the UK from 2001 to present.

Citations	Comments
Leslie, Mencuccini and Perks (2014b)	Obervations of frost damage from a trial in Cumbria. *E. gunnii* found to be more cold-tolerant than *E. nitens* and larger trees generally showed less damage in the early stages of the winter. (Chapter 4.2 of this thesis).
Leslie, Mencuccini and Perks (2014a)	An assessment of a trial in Devon of cold-tolerant eucalypts. *E. subcrenulata*, Mount Cattley provenance showed high survival and strong growth. Individuals only survival of *E. nitens.* (Chapter 3.2 of this thesis)
Leslie, Mencuccini and Perks (2013)	An assessment of three trials established in 1985 of snow gums and other cold-tolerant eucalypts. (Chapter 3.1 of this thesis).
Leslie, Mencuccini and Perks (2012)	A review of information on potential of eucalypts as a source of wood fuel in the UK. (Chapter 2.2 of this thesis).
Leslie, Mencuccini and Perks (2011)	A history of eucalypts in the British Isles (Chapter 2.1 of this thesis).
Black (unpublished data)	This was an unpublished, incomplete, draft report on a study of cold tolerance of eight species of eucalypts. Shoots were subjected to temperatures from -5°C to -18°C and the lethal temperature of 50% (LT50) was determined for each species. This was undertaken over two seasons and a score using seasonal variation in cold tolerance and absolute cold tolerance was developed. The best species in terms of this measure of cold tolerance were *E. glaucescens*, *E. rodwayi* and *E. subcrenulata*. *E. gunnii* was less tolerant and *E. nitens* was the least tolerant species tested.
McKay (2011) (Ed)	This was a collection of chapters on short rotation forestry including information on eucalypts. The initial chapters discuss short rotation forestry in general, but later ones describe growth and yield, mammal damge and risk of damage from pests and pathogens in relation to eucalypts in addition to other genera.
Kerr and Evans (2011)	Four sites in southern England of fast growing broadleaves, including *E. gunnii*, *E. archeri* and *E. glaucescens* planted at 1.4 and 2.8 m spacings. The findings confirmed that high productivity from eucalypts is possible but rarely achieved on large areas and across sites. A further finding was the considerable effect of spacing on biomass production, with teh closer spacing producing five times the biomass in *E. gunnii* over a 7 year period.
Harrison (2011)	This publication presented an update of results from a series of six short rotation forestry trials (five of which had been planted by that date) following the severe winter of 2009-2010 and 2010-2011. Of the eucalypts, *E. nitens* was killed completely across all the trials, but *E. gunnii* survived in all but one of the English trials and *E. glaucescens* survived in those in southern England.

Purse (2009a, 2009b)	Two short papers on observations from visits to Forestry Commission eucalypt trials.
Neilan and Thompson (2008)	A review of results from trials established in the Republic of Ireland from the 1930s to present day. The results of the trials established in the 1930s highlighted the rapid early growth of *E. johnstonii* but the faster growth of *E. urnigera, E. dalrympleana* and *E.radiata* over longer rotations. Height growth of *E. gunnii* and *E. delegatensis* at trials established in the 1990s was over 1 m per year and survival was very good, while that of *E. nitens* was more than 1.3 m per year over eight years. The cold tenderness of *E. nitens* was noted as a constraint.
Cope, Leslie and Weatherall (2008)	Results of an assessment of a trial of *E. gunnii* provenances at Glenbranter in central west Scotland. This, with previous studies (Evans 1986) confirmed Lake MacKenzie provenances perform well in Britain.
Bennet and Leslie (2003)	Results of an assessment at 21 years after planting of a trial of cold tolerant eucalypts at Thetford Chase in Suffolk, south west England. Survival was highest for provenances of *E. gunnii* and the closely related *E. archeri*. Growth of *E. glaucescens* was also relatively rapid, although survival was poorer. No individuals of the one provenance of *E. nitens* had survived.
Purse and Richardson (2001)	This paper provides notes on eight Forestry Commission trials visited in 2000 with a description of the performance of *E. pauciflora*, *E, gunnii*, *E, nitens* and *E. delegatensis*. A description of results from two private trials and also notes on programmes in France and Chile are provided.A conclusion was that dry yields of 10-15 odt ha^{-1} y^{-1} on rotations of 8 to 10 years were possible using eucalypts in Britain.

Table A1.2 Key publications on eucalypts relevant to the UK from 1980 to 2000.

Forrest and Moore (2000)	This paper describes the results from the fourteenth annual harvest from a planting of *E. gunnii* coppice in Ireland. This annual harvest was estimated at 15.4 t dry matter ha^{-1}.
Benson (1994)	This article provides anecdotal notes on eleven of the hardiest eucalypts in Britain, comprising; *E. debeuzevillei*, *E. niphophila*, E. *coccifera, E. pauciflora, E. archeri, E. gunnii, E. parvifolia, E. perriniana, E. vernicosa, E. subcrenulata and E. glaucescens*.
Mitchell et al (1993)	A report that describes results of experiments of short rotation coppice from eleven trials from Devon to Inverness-shire. Plots were planted with *E. gunnii,* poplar clones and also *Alnus rubra.* Despite survival dropping to between 54% and 72% in plots, *E. gunnii* produced by far the highest biomass yields of all species tested at about 18 odt ha^{-1} y^{-1} after 4 years of growth.
Potter (1990)	This report describes the results of seven experiments of short rotation coppice across Great Britain. Six species of hardwoods were tested, including a hybrid willow clone, a hybrid poplar clone, *Alnus cordata*, *Eucalyptus archeri* and also two species of *Nothofagus*. Some plots failed and the species were replaced by another willow clone or *Alnus glutinosa* or *Alnus rubra*. While *Nothofagus* failed completely, *E. archeri* grew rapidly inititially, but later suffered severe damage from winter cold and alsosilver leaf disease (*Chondrostereum pupereum*).
Evans (1986)	An update of Evans (1983) describing later results of trials. This noted that research should focus on the most hardy orignins; certain provanances of *E. gunnii*, *E. debeuzevillei* and *E. niphophila* were survived temperatures of between -19°C and -23°C during the winter of 1981/82. Work on vegetative propagation of individuals of eucalypts that had survived to temperatures lower than -19°C had been started at Alice Holt research station.
Evans	Results of trials following the extremely cold winter of 1981/82 where

(1983)	provenances of *E. debeuzevillei*, *E. gunnii* and *E. niphophila* had sufficient cold-tolerance to warrant further study.
Evans, Haydon and Lazzeri (1983)	An aticle on experience of nursery propagation of eucalypts in Britain. Recommendations were also provided on appropriate establishment methods, planting sites and size of planting stock.
Brooker and Evans (1983)	A key to the eucalypts found in Britain and Ireland with notes on habit, growth, cold-hardiness and considerations relating to establishment.
Evans (1980a)	A summary of information on eucalypt species growing in Britain, with recommendations on which may have potential for production forestry in Britain. Initial evidence suggested that *E. archeri*, *E. niphophila*, high altitude origins of *E. coccifera, E. debeuzevillei*, *E. glaucescens* and *E. gunnii* may be promising.

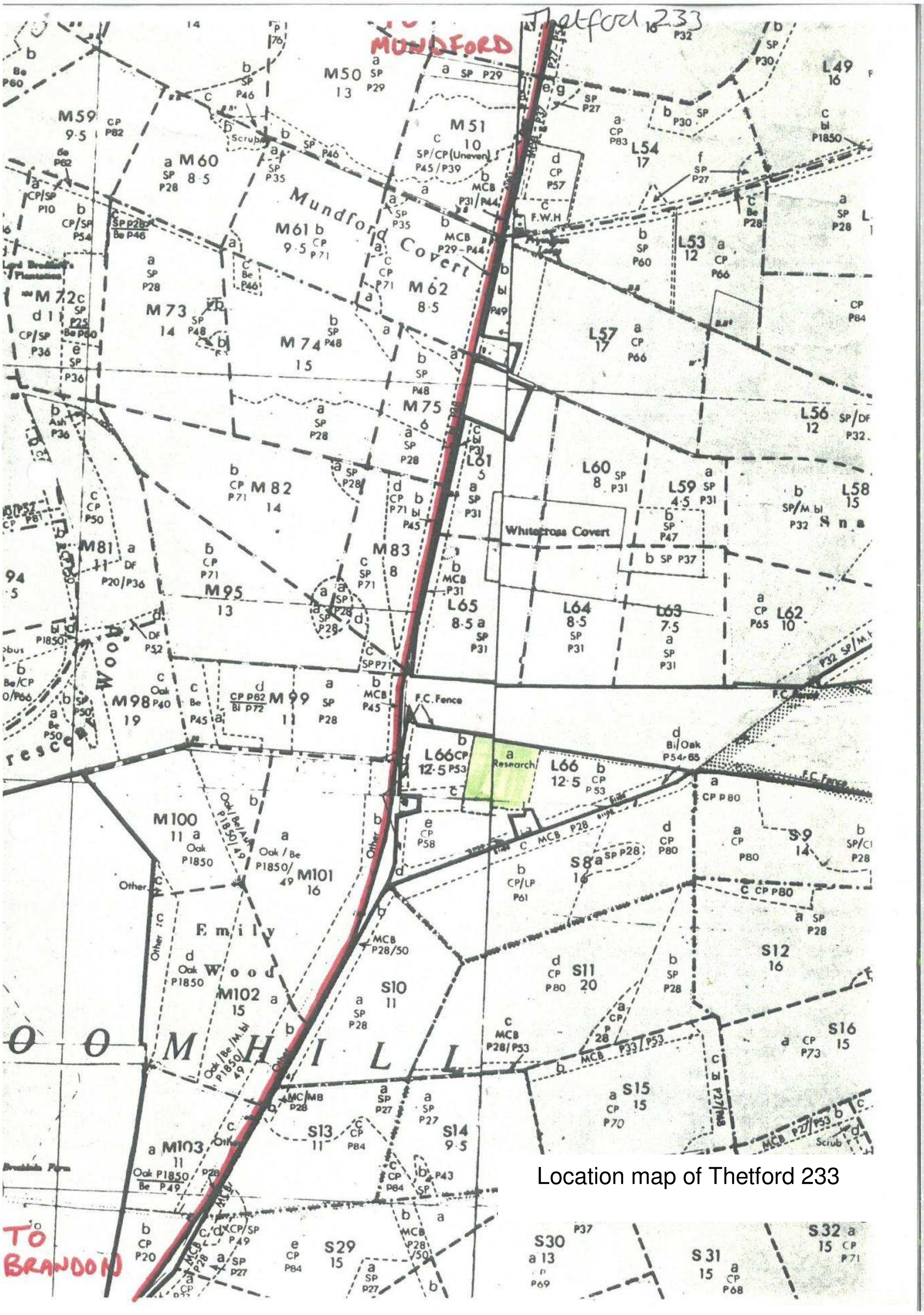
Table A1.3 Key publications on eucalypts relevant to the UK from 1950 to 1979

Marriage (1977)	An account of growth at a trial planting of individual eucalypts and other trees on a fairly mild site at an altitude of 120-150 m on the Devon/ Dorset border. Of fourty trees tested the fastest growing six were all eucalypts and *E. macarthuri* and *E, glaucescens* showed particularly rapid growth.
Halliwell (1974)	A description of eucalypts in general with, at the end, an assessment from personal observations of the hardiness of a range of species for planting in gardens. *E. gunnii* and *E. niphophila* are identified as tolerating cold down to -18°C, while *E. perriniana, E. urnigera, E. johnstonii, E. pauciflora, E. parvula, E. glaucescens, E. vernicosa* and *E. delegatenisi*s should tolerate temperatures of down to -15°C.
Barnard (1968)	A general discussion on eucalypts and the variation in their cold-tolerance recommending use of alpine provenances in the UK. Some failures are attributed to poor planting practice and prescriptions are given. The opportunity for hybridisation to produce trees suited to timber or pulp wood is also briefly discussed.
MacDonald et al (1964)	A thorough review of the status and potential of exotic broadleaved and coniferous trees for forestry in Britain.This included a section on eucalypts, includining a table of minimum temperatures killed or survived for over seventy species. The bulletin also contains a table of growth records for five species. The general conclusion was that eucalypts have limited potential in Britain and that a -12°C (10°F) absolute minimum isotherm sets the boundaries for reasonable prospects for growing eucalypts successfully.
Martin (1950)	This article described observations of growth and survival of eucalypts from a number of sites in the United Kingdom and the Republic of Ireland. The most hardy eucalypts identified were E*. gunnii, E. niphophila, E. parvula* and *E. vernicosa*. *E. coccifera* was considered slightly less hardy with *E. urnigera*, *E. subcrenulata* and *E. johnstonii* being less hardy still. The article ends with the speculation that there is a high probability that certain species or hybrids of eucalypts could play a role in production forestry in the UK

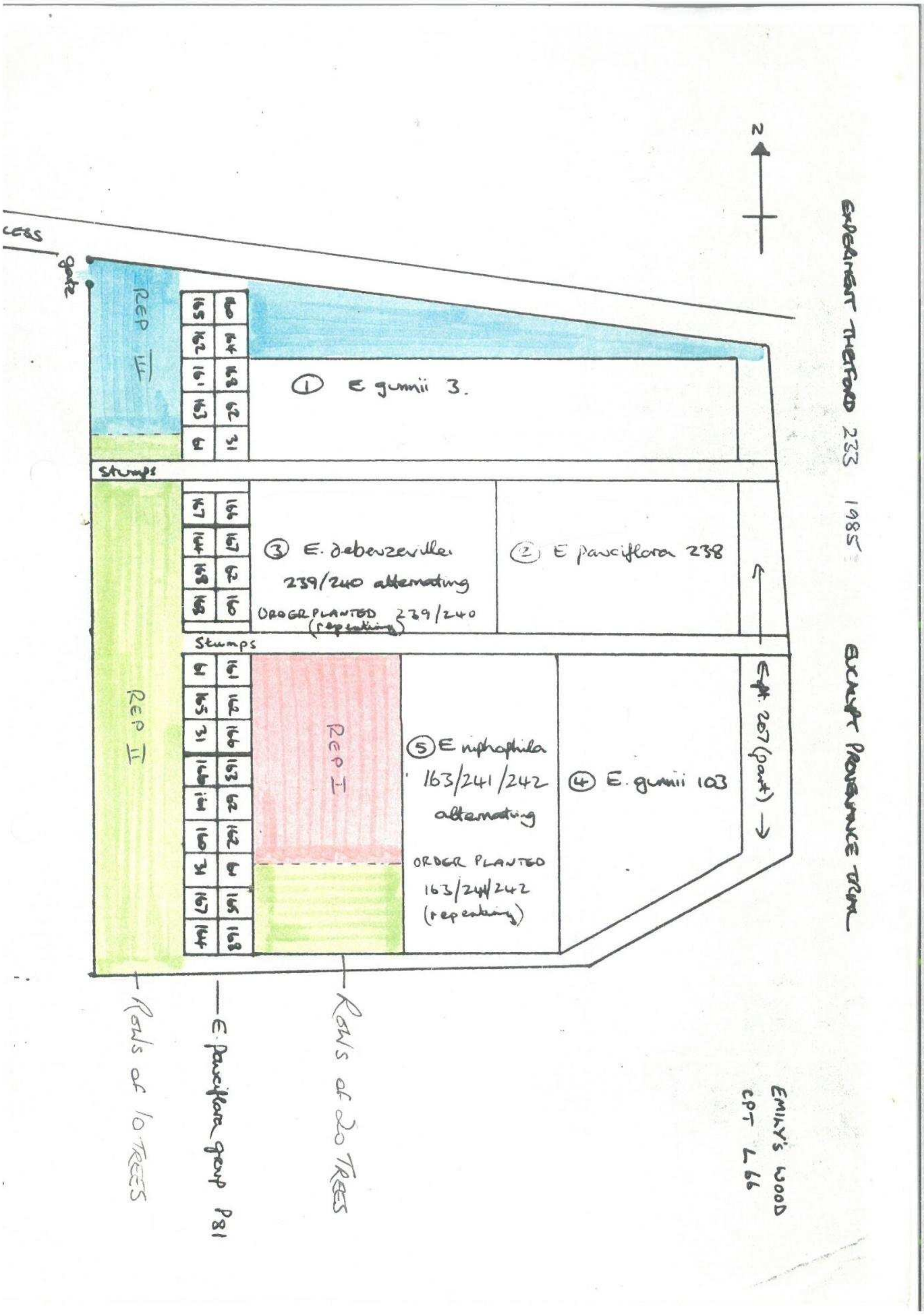
Appendix 2 Layouts of the trials

Appendix 2.1 Layouts of snow gums trials

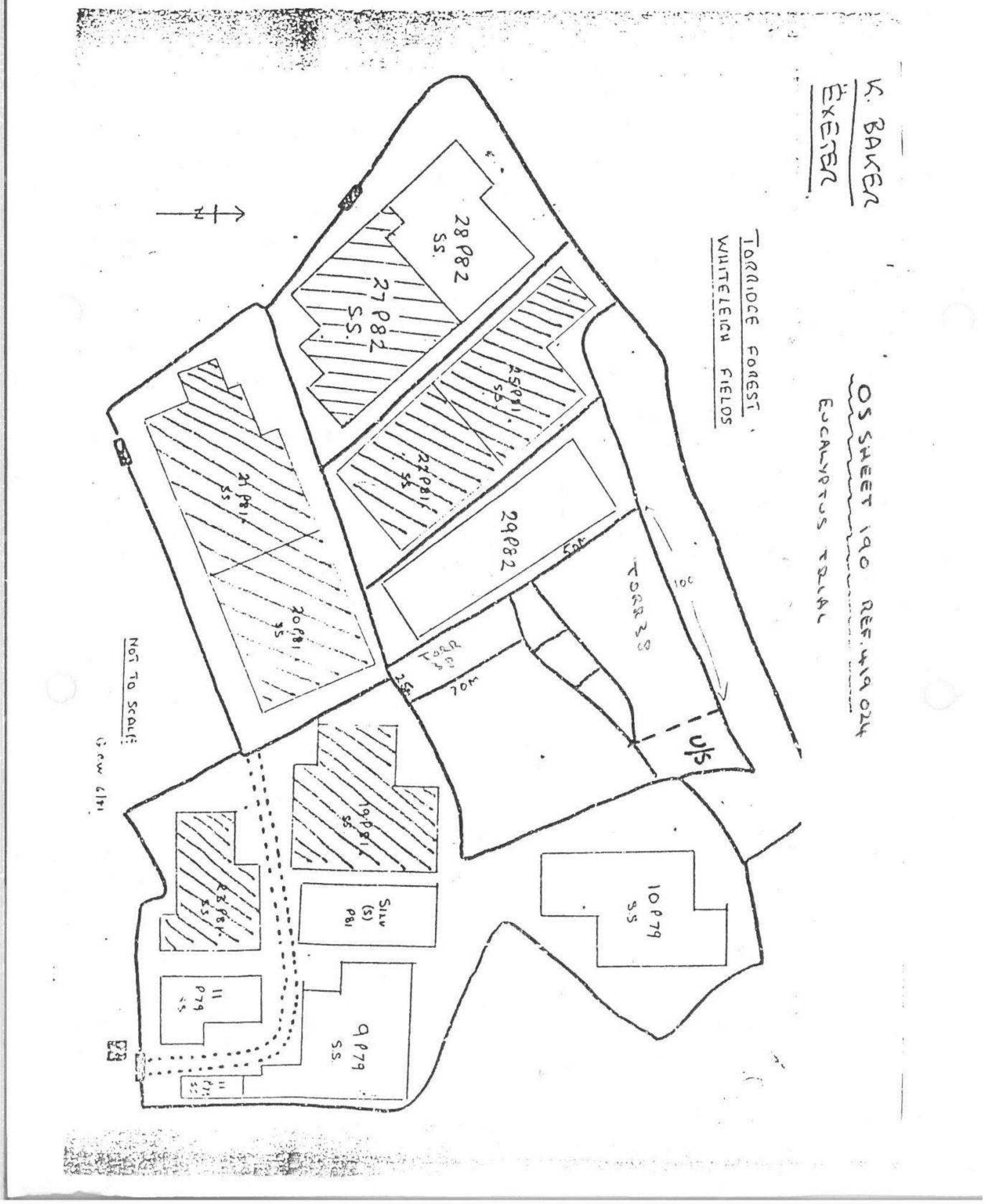
Location and Layout of the Thetford trial

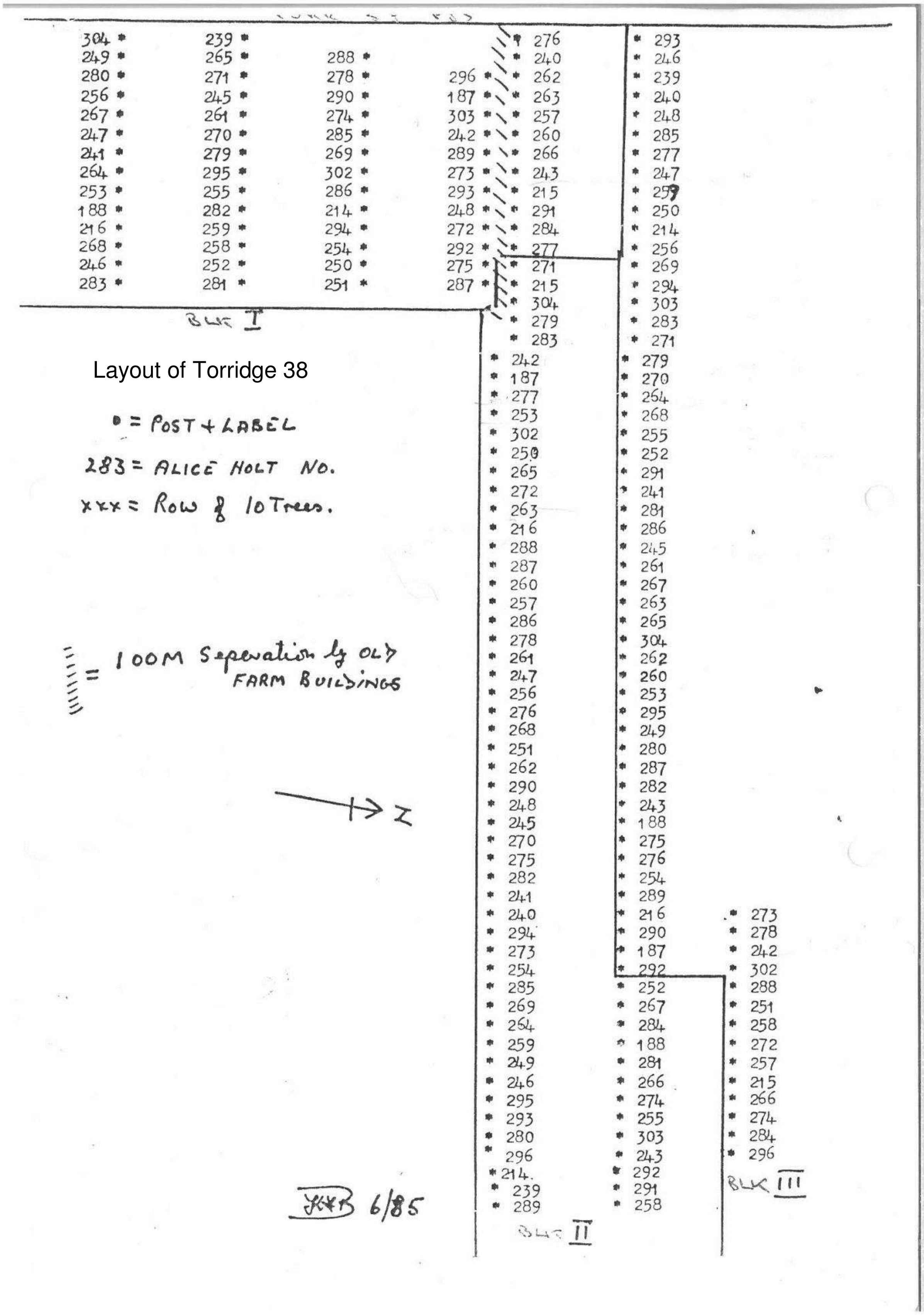


Location map of Thetford 233


EXPERIMENT THETFORD 233 1985
EUCALYPT PROVENANCE TRIAL
EMILY'S WOOD CPT L66
N
CESS
gate
REP III
REP II
REP I
Stumps
Stumps
① E gunnii 3.
② E pauciflora 238
③ E. debeuzevillei 239/240 alternating
ORDER PLANTED 239/240 (repeating)
④ E. gunnii 103
⑤ E niphophila 163/241/242 alternating
ORDER PLANTED 163/241/242 (repeating)
Expt. 267 (part)
Rows of 10 TREES
E. pauciflora group P81
Rows of 20 TREES

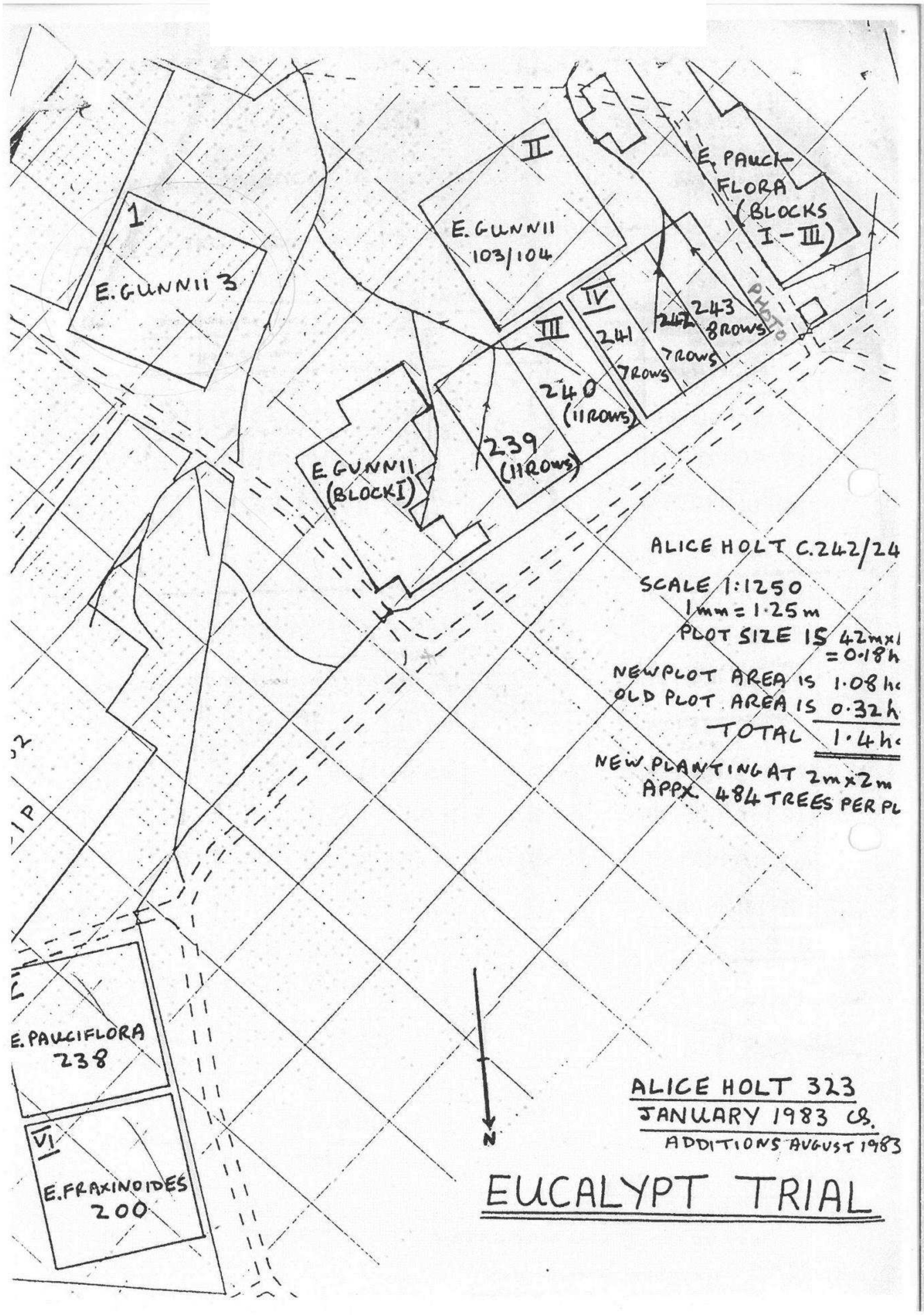
Location and layout of Torridge trial

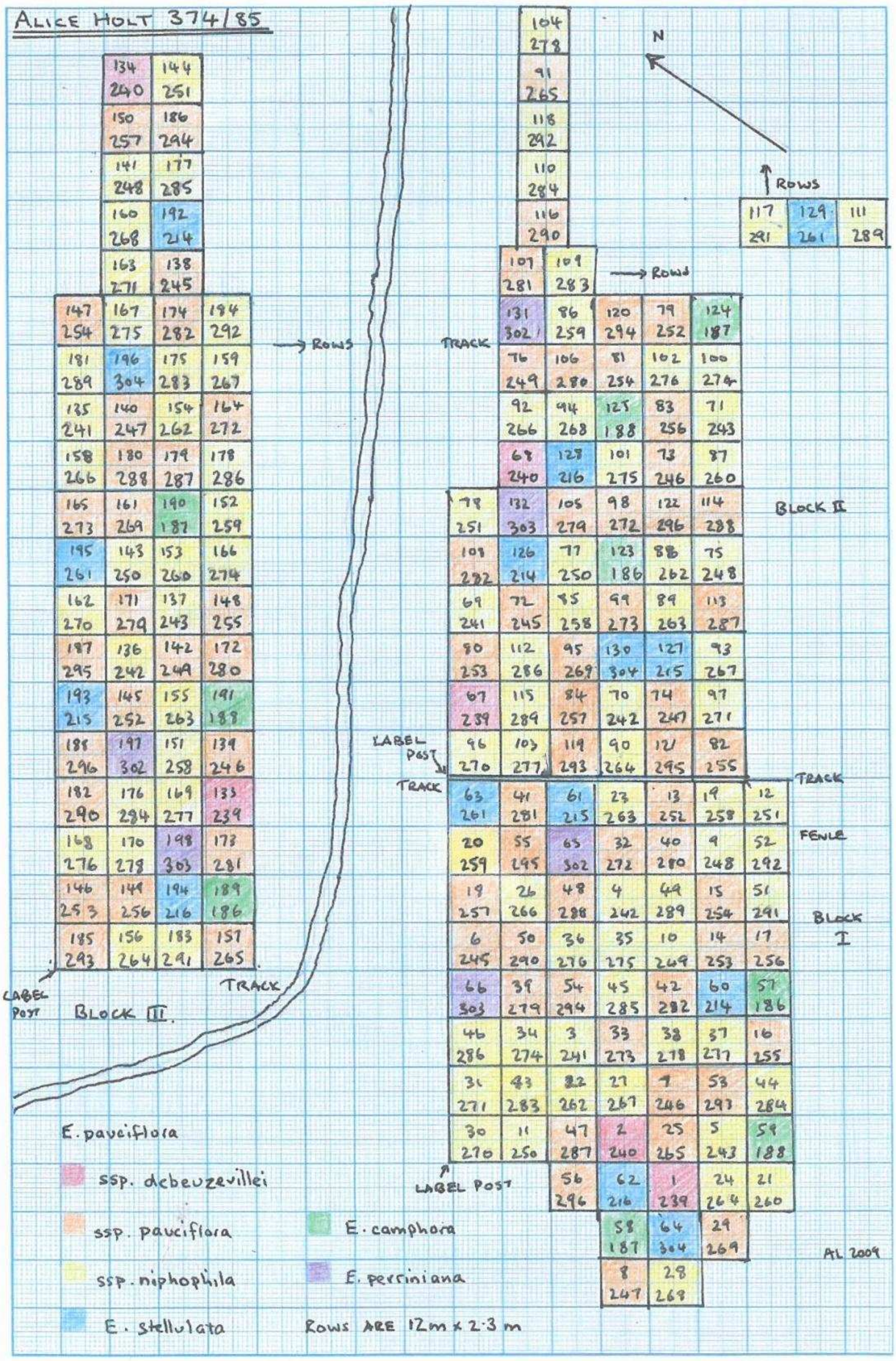




Layout of Torridge 38

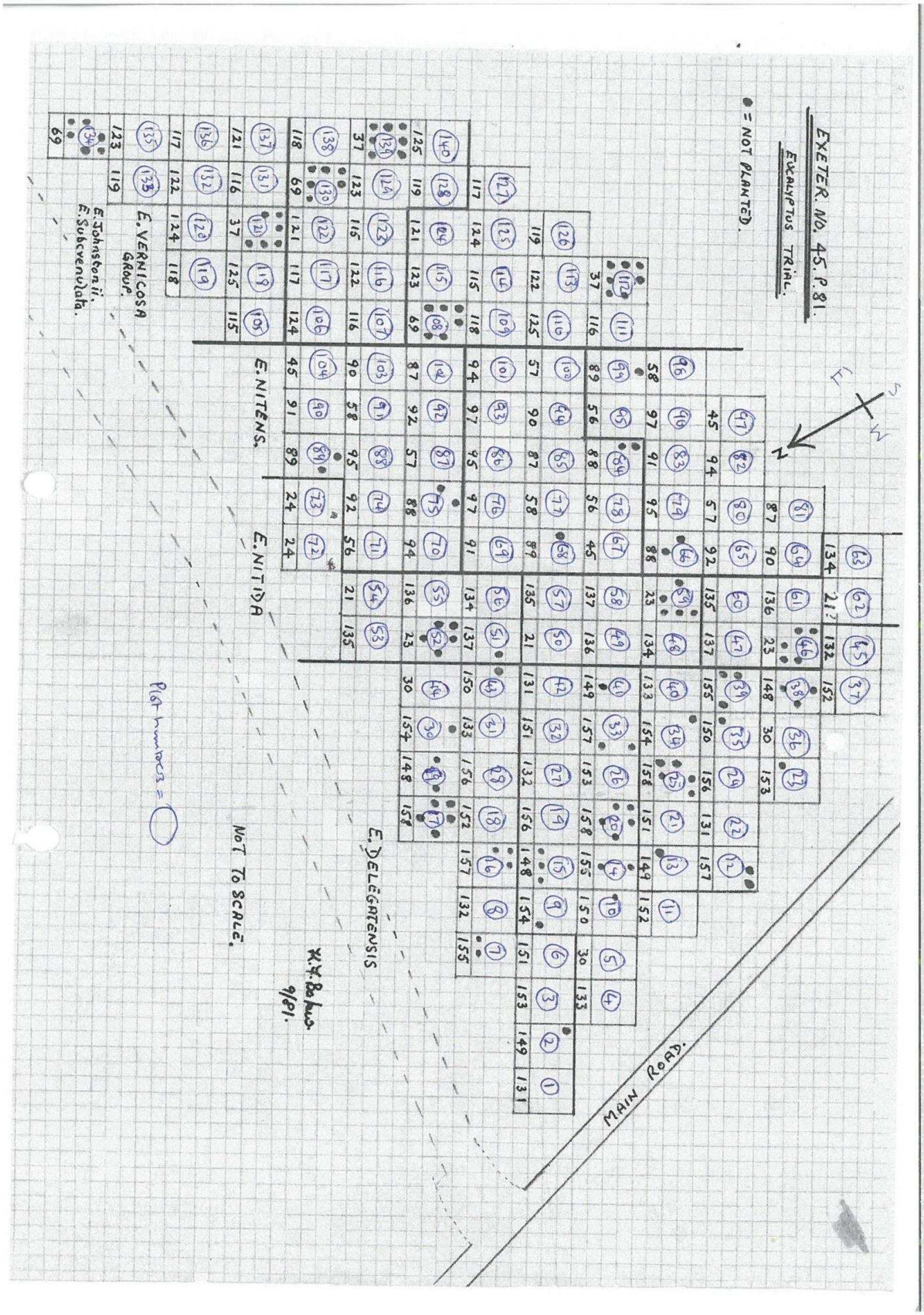
Location and Layout of Chiddingfold trial





ALICE HOLT 374/85
N
ROWS
ROWS
ROWS
TRACK
TRACK
TRACK
LABEL POST
LABEL POST
LABEL POST
FENCE
BLOCK I
BLOCK II
BLOCK III
E. pauciflora
ssp. debeuzevillei
ssp. pauciflora
ssp. niphophila
E. stellulata
E. camphora
E. perriniana
ROWS ARE 12m x 2·3 m
AL 2009

Appendix 2.2 Layout of Exeter (Chudleigh) trial



Appendix 2.3 Layout of Newton Rigg trial

The trial comprised a randomised complete block design with six treatments and six blocks (replications)

Direction of slope

					Block
(1) Ap	(2) Fe	(3) En	(4) Eg	(5) Ag	
(10) Fe	(9) Eg	(8) Ag	(7) En	(6) Ap	II
(11) Ap	(12) Ag	(13) Fe	(14) En	(15) Eg	III
(20) Eg	(19) En	(18) Ap	(17) Fe	(16) Ag	IV
(21) Ap	(22) Eg	(23) En	(24) Fe	(25) Ag	V
(30) Ag	(29) Eg	(28) Ap	(27) En	(26) Fe	VI

The numbers in brackets denote the plot numbers and the two letter codes the species:

Ag = *Alnus glutinosa*, Ap = *Acer pseudoplatanus*, Eg = *Eucalyptus gunnii*, En = *Eucalyptus nitens*, Fe = *Fraxinus excelsior.*

Plots were 10 x 8 trees with the inner 6 x 8 trees being measured. The numbering of trees in the plots and sequence for measuring is shown below:

x	x	x	x	x	x	x	x
x	1	16	17	32	33	48	x
x	2	15	18	31	34	47	x
x	3	14	19	30	35	46	x
x	4	13	20	29	36	45	x
x	5	12	21	28	37	44	x
x	6	11	22	27	38	43	x
x	7	10	23	26	39	42	x
x	8	9	24	25	40	41	x
x	x	x	x	x	x	x	x

Appendix 3 Origins tested in the snow gums trials

Appendix 3.1 Details of origins of *Eucalyptus pauciflora* subspecies

(Forestry Commission Research and Development Division 1985)

Alice Holt number	Species & CSIRO number	Locality	Latd	Longtd	Altitude
239	*debeuzevillei*	Mt Ginini ACT	35°32	35°35'	1745
240	*debeuzevillei*	Mt Gingera ACT	35°35'	148°47'	1750
241	*niphophila*	Mt. Coree, ACT	35°19'	148°49'	1390
242	*niphophila*	Mt. Franklin	35°30'	148°47'	1630
243	*niphophila*	Mt. Ginini ACT	35°30'	148°47'	1740-1760
245, 246, 247, 249, 252, 253, 254	*pauciflora*	Mt. Bogong	E,E,W,W, W, W, NW		1780, 1800, 1740, 1780, 1800, 1770, 1730
248, 250, 251	*niphophila*	Mt. Bogong	W, W		1830, 1860,1830
255, 256, 257	*pauciflora*	Currango Plain	N, W, not specified		1320, 1300, 1340
258, 259, 260	*niphophila*	Currango Plain	W,W,not specified		1310, 1270, 1260
262, 263, 264, 266, 267, 268, 270, 271	*niphophila*	Mt. Hotham	SE, NE, E, SE, NE, E, N,N		1725, 1680, 1760, 1700, 1775, 1760, 1790, 1760
265, 269	*pauciflora*	Mt. Hotham	SE, N		1660, 1765
272, 273	*pauciflora*	Kiandra Plain	E,E		1454, 1300
274, 275, 276	*niphophila*	Kiandra Plain	W,SW,E		1524, 1460, 1400
277, 278	*niphophila*	Langford Gap	SW,SW		1650,1620
279, 280, 281	*pauciflora*	Langford Gap	NE, NE, NE		1640, 1660, 1680
282	*pauciflora*	Nungar Place	E		1270
283, 284, 285, 286	*niphophila*	Nungar Plain	E, SW, W,W		1300,1300, 1280, 1330
287, 288, 289, 291	*niphophila*	Ramshead	SE, SW, SE		1828, 1890, 1870, 1870

290	*pauciflora*	Ramshead	N	1885
292	*niphophila*	Ramshead Ridge	S	1890
293, 294	*pauciflora*	Ramshead Ridge	S, S	1980, 1970
295, 296	*pauciflora*	Thredbo Valley	S,S	1640, 1700

Appendix 3.2 Details of origins of other *Eucalyptus* species

(Forestry Commission Research and Development Division 1985)

Alice Holt number	Species & CSIRO number	Locality	Latd	Longtd	Altitude
187	*camphora*	Tamut	35°30'	148°06'	1100
188	*camphora*	Coree Flat	35°21'	148°44'	1000
221	*viminalis*	Big Badja Mts	36°01'	149°34'	1380
214	*stellulata*	Nimmitabel	36°33'	149°22'	1070
215	*stellulata*	W.Berridale	36°21'	148°46	1040
216	*stellulata*	S. Jerangle	35°54'	149°22'	1200
261	*stellulata*	Currango Plain	Not available	Not available	Not available
302	*perriniana*	Smiggin Hole	36°22'	148°24'	1555
303	*perriniana*	Kiandra	35°53'	148°24'	1500
304	*stellulata*	Cotter Flats	35°38'	148°24'	1000

Appendix 4 Statistical supporting data for snow gums trials.

Appendix 4.1 Comparison of variables across three trials

1=Thetford, 2= Chiddingfold, 3= Torridge

Tests of Normality

	Trial	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Height	1.00	.037	159	.200*	.985	159	.078
	2.00	.084	130	.027	.945	130	.000
	3.00	.059	181	.200*	.980	181	.010
Basalarea	1.00	.143	159	.000	.756	159	.000
	2.00	.184	130	.000	.774	130	.000
	3.00	.159	181	.000	.740	181	.000
LNBasalarea	1.00	.057	159	.200*	.979	159	.017
	2.00	.045	130	.200*	.988	130	.293
	3.00	.076	181	.012	.964	181	.000
Survival	1.00	.144	159	.000	.940	159	.000
	2.00	.155	130	.000	.903	130	.000
	3.00	.126	181	.000	.949	181	.000
Asinsvvl	1.00	.130	159	.000	.952	159	.000
	2.00	.129	130	.000	.907	130	.000
	3.00	.114	181	.000	.953	181	.000
Stems	1.00	.161	159	.000	.866	159	.000
	2.00	.277	130	.000	.792	130	.000
	3.00	.179	181	.000	.814	181	.000
BAperha	1.00	.143	159	.000	.756	159	.000
	2.00	.184	130	.000	.774	130	.000
	3.00	.159	181	.000	.740	181	.000

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

The data were significantly different from normal so a non parametric Kruskal Wallis test was used to examine differences between height, plot basal area, survival and number of stems.

Ranks

	Trial	N	Mean Rank
Height	1.00	164	271.29
	2.00	136	185.05
	3.00	181	255.60
	Total	481	
Basalarea	1.00	170	282.25
	2.00	138	238.02
	3.00	182	216.84
	Total	490	
Survival	1.00	198	313.69
	2.00	195	235.86
	3.00	198	337.53
	Total	591	
Stems	1.00	171	293.41
	2.00	152	193.09
	3.00	185	268.99
	Total	508	

Test Statistics[a,b]

	Height	Basalarea	Survival	Stems
Chi-Square	31.821	19.291	38.680	42.060
df	2	2	2	2
Asymp. Sig.	.000	.000	.000	.000

a. Kruskal Wallis Test

b. Grouping Variable: Trial

Appendix 4.2 Testing of differences between origins in height, basal area, survival and number of stems for the three trials.

There were more than 60 origins and SPSS cannot test heterogeneity of variances for more than 50 origins. As such it was not possible to check this assumption that underpins the use of ANOVA. To test differences across all origins, a non parametric approach (Kruskal Wallis) was adopted that did not require normality or equality of variances.
Rank data has been omitted due to the large number of entries but the test statistics are presented for each trial below:

Thetford

Test Statistics[a,b]

	Height	Basalarea	Survival	Stems
Chi-Square	74.051	100.211	94.672	91.987
df	61	62	64	62
Asymp. Sig.	.122	.002	.008	.008

a. Kruskal Wallis Test
b. Grouping Variable: Origin

Torridge

Test Statistics[a,b]

	height	basalarea	Survival	Stems
Chi-Square	84.702	86.257	87.274	93.680
df	61	61	62	61
Asymp. Sig.	.024	.018	.019	.005

a. Kruskal Wallis Test
b. Grouping Variable: Origin

Chiddingfold

Test Statistics[a,b]

	Height	Basalarea	Survival	Stems
Chi-Square	83.962	88.329	79.471	111.029
df	63	63	64	63
Asymp. Sig.	.040	.019	.092	.000

a. Kruskal Wallis Test
b. Grouping Variable: Origin

Appendix 4.3 Thetford, comparison of best survival origins by origin

Tests of Normality[b]

	Origin	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
height	239.00	.314	3	.	.893	3	.363
	243.00	.292	3	.	.923	3	.463
	248.00	.298	3	.	.915	3	.436
	251.00	.260	2	.			
	256.00	.250	3	.	.967	3	.651
	264.00	.184	3	.	.999	3	.927
	267.00	.302	3	.	.911	3	.420
	271.00	.345	3	.	.839	3	.213
	273.00	.260	2	.			
	276.00	.176	3	.	1.000	3	.980
	277.00	.304	3	.	.907	3	.407
	281.00	.263	3	.	.956	3	.595
	283.00	.310	3	.	.899	3	.383
	288.00	.301	3	.	.911	3	.421
	290.00	.247	3	.	.969	3	.664
	291.00	.364	3	.	.799	3	.112
	292.00	.273	3	.	.945	3	.549
	293.00	.299	3	.	.915	3	.433
	295.00	.324	3	.	.876	3	.313
	296.00	.365	3	.	.797	3	.107
Basalarea	239.00	.281	3	.	.937	3	.515
	243.00	.250	3	.	.967	3	.650
	248.00	.295	3	.	.920	3	.451
	251.00	.260	2	.			
	256.00	.204	3	.	.993	3	.843
	264.00	.238	3	.	.976	3	.701
	267.00	.186	3	.	.998	3	.918
	271.00	.214	3	.	.989	3	.803
	273.00	.260	2	.			
	276.00	.223	3	.	.985	3	.764
	277.00	.372	3	.	.782	3	.072
	281.00	.179	3	.	.999	3	.950
	283.00	.209	3	.	.991	3	.823
	288.00	.303	3	.	.909	3	.413
	290.00	.364	3	.	.800	3	.113
	291.00	.325	3	.	.875	3	.309
	292.00	.343	3	.	.843	3	.221
	293.00	.260	3	.	.958	3	.607
	295.00	.378	3	.	.768	3	.039
	296.00	.339	3	.	.851	3	.243
Survival	239.00	.175	3	.	1.000	3	1.000
	243.00	.385	3	.	.750	3	.000
	248.00	.175	3	.	1.000	3	1.000
	251.00	.260	2	.			
	256.00	.175	3	.	1.000	3	1.000
	264.00	.328	3	.	.871	3	.298
	267.00	.385	3	.	.750	3	.000
	271.00	.253	3	.	.964	3	.637
	273.00	.260	2	.			
	276.00	.314	3	.	.893	3	.363
	277.00	.292	3	.	.923	3	.463
	281.00	.175	3	.	1.000	3	1.000

	283.00	.385	3	.	.750	3	.000
	288.00	.292	3	.	.923	3	.463
	291.00	.385	3	.	.750	3	.000
	292.00	.385	3	.	.750	3	.000
	293.00	.175	3	.	1.000	3	1.000
	295.00	.292	3	.	.923	3	.463
	296.00	.253	3	.	.964	3	.637
Stems	239.00	.385	3	.	.750	3	.000
	243.00	.292	3	.	.923	3	.463
	248.00	.196	3	.	.996	3	.878
	251.00	.260	2	.			
	256.00	.253	3	.	.964	3	.637
	264.00	.204	3	.	.993	3	.843
	267.00	.338	3	.	.853	3	.249
	271.00	.232	3	.	.980	3	.726
	273.00	.260	2	.			
	276.00	.219	3	.	.987	3	.780
	277.00	.334	3	.	.860	3	.266
	281.00	.314	3	.	.893	3	.363
	283.00	.175	3	.	1.000	3	1.000
	288.00	.373	3	.	.780	3	.067
	290.00	.204	3	.	.993	3	.843
	291.00	.236	3	.	.977	3	.712
	292.00	.214	3	.	.989	3	.802
	293.00	.241	3	.	.974	3	.688
	295.00	.216	3	.	.989	3	.795
	296.00	.385	3	.	.750	3	.000

a. Lilliefors Significance Correction
b. Survival is constant when Origin = 290.00. It has been omitted.

The height, basal area, survival and stems data are not significantly different from normal.
However variances even when data are transformed are not equal except for height.

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Survival	1.870	19	39	.049
Basalarea	4.781	19	38	.000
height	1.572	19	38	.116
Stems	2.145	19	38	.022
LNBA	2.620	19	38	.006
Arcsinsvvl	2.498	19	39	.008

For height conduct an ANOVA:

ANOVA

height

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	164.870	19	8.677	.892	.594
Within Groups	369.612	38	9.727		
Total	534.482	57			

Differences are not significant.
For other variables, they are normally distributed but variances are unequal so an ANOVA is inappropriate and a Kruskal Wallis test is used to detect overall differences between origins:

Test Statistics[a,b]

	Basalarea	Stems	Survival
Chi-Square	32.367	20.972	12.346
df	19	19	19
Asymp. Sig.	.028	.338	.870

a. Kruskal Wallis Test
b. Grouping Variable: Origin

Basal area showed significant differences. As normally distributed but variances differ a Games Howell test can be applied. There were only two origins that were significantly different from one another, (1) 267 and 256 and (2) 267 and 283 (others not shown as large amount of data):

Multiple Comparisons

Dependent Variable: Basalarea

Games-Howell

(I) Origin	(J) Origin	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
267.00	239.00	-.05930	.03275	.852	-.4455	.3269
	243.00	-.05910	.03137	.832	-.4288	.3106
	248.00	-.00760	.00625	.979	-.0719	.0567
	251.00	-.01892	.01324	.920	-.5379	.5001
	256.00	-.01853*	.00256	**.040**	-.0359	-.0012
	264.00	-.00430	.00733	1.000	-.0825	.0739
	271.00	-.01080	.00905	.980	-.1108	.0892
	273.00	-.03737	.00457	.195	-.1486	.0738
	276.00	.00287	.00563	1.000	-.0534	.0591
	277.00	-.02713	.01383	.810	-.1862	.1319
	281.00	-.01027	.00595	.880	-.0707	.0502
	283.00	-.02397*	.00312	**.047**	-.0475	-.0004
	288.00	-.00077	.00457	1.000	-.0431	.0416
	290.00	-.03327	.01371	.675	-.1909	.1244
	291.00	-.00060	.00408	1.000	-.0364	.0352
	292.00	-.01603	.00452	.386	-.0577	.0256
	293.00	-.00220	.00263	1.000	-.0203	.0159
	295.00	-.03887	.02381	.899	-.3182	.2405
	296.00	-.03493	.00746	.257	-.1148	.0450

Appendix 4.4 Thetford, comparison of best survival origins by block

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Block	Statistic	df	Sig.	Statistic	df	Sig.
Height	1	.085	53	.200*	.971	53	.223
	2	.081	56	.200*	.978	56	.387
	3	.136	50	.021	.892	50	.000
Basalarea	1	.177	53	.000	.900	53	.000
	2	.130	56	.020	.897	56	.000
	3	.250	50	.000	.628	50	.000
LNBasalarea	1	.106	53	.200*	.960	53	.073
	2	.103	56	.200*	.955	56	.035
	3	.102	50	.200*	.977	50	.417
Survival	1	.166	53	.001	.933	53	.005
	2	.144	56	.006	.929	56	.003
	3	.156	50	.004	.934	50	.008
Asinsvvl	1	.168	53	.001	.941	53	.011
	2	.123	56	.035	.944	56	.011
	3	.136	50	.021	.948	50	.029
Stems	1	.141	53	.011	.896	53	.000
	2	.159	56	.001	.872	56	.000
	3	.237	50	.000	.765	50	.000
LNheight	1	.122	53	.047	.887	53	.000
	2	.115	56	.063	.947	56	.016
	3	.105	50	.200*	.972	50	.273

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

None of the variables conformed across all three blocks to a normal distribution so non-parametric Kruskal Wallis tests were used to detect significant differences between blocks.

Ranks

	Block	N	Mean Rank
Origin	1	66	99.50
	2	66	99.50
	3	66	99.50
	Total	198	
Height	1	53	98.21
	2	56	80.61
	3	50	60.02
	Total	159	
Basalarea	1	55	81.94
	2	56	91.56
	3	56	78.46
	Total	167	
Stems	1	55	92.16
	2	56	88.63
	3	56	71.36
	Total	167	

Test Statistics[a,b]

	Origin	Height	Basalarea	Stems
Chi-Square	.000	17.717	2.204	6.031
df	2	2	2	2
Asymp. Sig.	1.000	.000	.332	.049

a. Kruskal Wallis Test

b. Grouping Variable: Block

Height and stems showed significant differences by block and so Mann Whitnet test were used to identify where differences originated:

Ranks

	Block	N	Mean Rank	Sum of Ranks
Height	1	53	61.60	3265.00
	2	56	48.75	2730.00
	Total	109		
Stems	1	55	57.00	3135.00
	2	56	55.02	3081.00
	Total	111		

Test Statistics[a]

	Height	Stems
Mann-Whitney U	1134.000	1485.000
Wilcoxon W	2730.000	3081.000
Z	-2.122	-.327
Asymp. Sig. (2-tailed)	.034	.744

a. Grouping Variable: Block

Ranks

	Block	N	Mean Rank	Sum of Ranks
Height	1	53	63.60	3371.00
	3	50	39.70	1985.00
	Total	103		
Stems	1	55	63.16	3474.00
	3	56	48.96	2742.00
	Total	111		

Test Statistics[a]

	Height	Stems
Mann-Whitney U	710.000	1146.000
Wilcoxon W	1985.000	2742.000
Z	-4.059	-2.348
Asymp. Sig. (2-tailed)	.000	.019

a. Grouping Variable: Block

Ranks

	Block	N	Mean Rank	Sum of Ranks
Height	2	56	60.36	3380.00
	3	50	45.82	2291.00
	Total	106		
Stems	2	56	62.11	3478.00
	3	56	50.89	2850.00
	Total	112		

Test Statistics[a]

	Height	Stems
Mann-Whitney U	1016.000	1254.000
Wilcoxon W	2291.000	2850.000
Z	-2.431	-1.852
Asymp. Sig. (2-tailed)	.015	.064

a. Grouping Variable: Block

Appendix 4.5 Torridge, comparison of best survival origins

Tests of Normality[b,c]

	Origin	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Height	239.00	.323	3	.	.878	3	.319
	240.00	.213	3	.	.990	3	.806
	242.00	.225	3	.	.984	3	.756
	248.00	.308	3	.	.902	3	.391
	267.00	.326	3	.	.874	3	.307
	271.00	.385	3	.	.750	3	.000
	302.00	.177	3	.	1.000	3	.971
	303.00	.177	3	.	1.000	3	.974
Basalarea	239.00	.182	3	.	.999	3	.937
	240.00	.275	3	.	.944	3	.543
	242.00	.345	3	.	.839	3	.212
	248.00	.259	3	.	.959	3	.609
	267.00	.257	3	.	.961	3	.619
	271.00	.335	3	.	.858	3	.263
	302.00	.372	3	.	.781	3	.070
	303.00	.206	3	.	.993	3	.837
LNbasalarea	239.00	.175	3	.	1.000	3	.997
	240.00	.182	3	.	.999	3	.935
	242.00	.324	3	.	.877	3	.314
	248.00	.217	3	.	.988	3	.790
	267.00	.211	3	.	.991	3	.817
	271.00	.321	3	.	.881	3	.328
	302.00	.376	3	.	.773	3	.051
	303.00	.255	3	.	.963	3	.629
Survival	239.00	.385	3	.	.750	3	.000
	240.00	.253	3	.	.964	3	.637
	242.00	.385	3	.	.750	3	.000
	248.00	.175	3	.	1.000	3	1.000
	267.00	.204	3	.	.993	3	.843
	271.00	.175	3	.	1.000	3	1.000
	302.00	.385	3	.	.750	3	.000
	303.00	.292	3	.	.923	3	.463
Arcsinsvvl	239.00	.385	3	.	.750	3	.000
	240.00	.302	3	.	.910	3	.417
	242.00	.385	3	.	.750	3	.000
	248.00	.175	3	.	1.000	3	1.000
	267.00	.214	3	.	.989	3	.802
	271.00	.189	3	.	.998	3	.907
	302.00	.385	3	.	.750	3	.000
	303.00	.297	3	.	.916	3	.440
Stems	239.00	.253	3	.	.964	3	.637
	240.00	.232	3	.	.980	3	.726
	242.00	.300	3	.	.913	3	.430
	248.00	.353	3	.	.824	3	.174
	267.00	.314	3	.	.893	3	.363
	271.00	.219	3	.	.987	3	.780
LNheight	239.00	.311	3	.	.898	3	.379
	240.00	.205	3	.	.993	3	.843
	242.00	.185	3	.	.998	3	.922
	248.00	.257	3	.	.961	3	.618
	267.00	.336	3	.	.856	3	.257
	271.00	.385	3	.	.750	3	.000
	302.00	.214	3	.	.989	3	.802
	303.00	.198	3	.	.995	3	.869

a. Lilliefors Significance Correction
b. Stems is constant when Origin = 302.00. It has been omitted.
c. Stems is constant when Origin = 303.00. It has been omitted.

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Height	1.681	7	16	.184
Basalarea	4.102	7	16	.009
LNbasalarea	1.947	7	16	.128
Survival	1.331	7	16	.299
Arcsinsvvl	2.143	7	16	.098
Stems	4.676	7	16	.005

For LN basal area the data were normally distributed and variances were equal so an ANOVA was appropriate.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LNbasalarea	Between Groups	10.618	7	1.517	4.338	.007
	Within Groups	5.594	16	.350		
	Total	16.212	23			

To compare origins a Tukey's post hoc test was performed on the data:

Multiple Comparisons

Dependent Variable: LNbasalarea
Tukey HSD

		Mean Difference			95% Confidence Interval	
(I) Origin	(J) Origin	(I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
239.00	240.00	.47276	.48280	.971	-1.1988	2.1443
	242.00	.59786	.48280	.908	-1.0736	2.2694
	248.00	1.86649*	.48280	.023	.1950	3.5380
	267.00	1.74569*	.48280	.037	.0742	3.4172
	271.00	1.87171*	.48280	.023	.2002	3.5432
	302.00	.79421	.48280	.719	-.8773	2.4657
	303.00	1.14468	.48280	.317	-.5268	2.8162
240.00	239.00	-.47276	.48280	.971	-2.1443	1.1988
	242.00	.12510	.48280	1.000	-1.5464	1.7966
	248.00	1.39373	.48280	.141	-.2778	3.0652
	267.00	1.27293	.48280	.212	-.3986	2.9444
	271.00	1.39895	.48280	.138	-.2726	3.0705
	302.00	.32145	.48280	.997	-1.3501	1.9930
	303.00	.67192	.48280	.848	-.9996	2.3434
242.00	239.00	-.59786	.48280	.908	-2.2694	1.0736
	240.00	-.12510	.48280	1.000	-1.7966	1.5464
	248.00	1.26862	.48280	.215	-.4029	2.9401
	267.00	1.14783	.48280	.314	-.5237	2.8193
	271.00	1.27385	.48280	.212	-.3977	2.9454
	302.00	.19635	.48280	1.000	-1.4752	1.8679
	303.00	.54682	.48280	.940	-1.1247	2.2183
248.00	239.00	-1.86649*	.48280	.023	-3.5380	-.1950
	240.00	-1.39373	.48280	.141	-3.0652	.2778
	242.00	-1.26862	.48280	.215	-2.9401	.4029
	267.00	-.12080	.48280	1.000	-1.7923	1.5507
	271.00	.00523	.48280	1.000	-1.6663	1.6767
	302.00	-1.07228	.48280	.389	-2.7438	.5992
	303.00	-.72180	.48280	.799	-2.3933	.9497
267.00	239.00	-1.74569*	.48280	.037	-3.4172	-.0742
	240.00	-1.27293	.48280	.212	-2.9444	.3986

	242.00	-1.14783	.48280	.314	-2.8193	.5237
	248.00	.12080	.48280	1.000	-1.5507	1.7923
	271.00	.12602	.48280	1.000	-1.5455	1.7975
	302.00	-.95148	.48280	.528	-2.6230	.7200
	303.00	-.60101	.48280	.906	-2.2725	1.0705
271.00	239.00	-1.87171*	.48280	.023	-3.5432	-.2002
	240.00	-1.39895	.48280	.138	-3.0705	.2726
	242.00	-1.27385	.48280	.212	-2.9454	.3977
	248.00	-.00523	.48280	1.000	-1.6767	1.6663
	267.00	-.12602	.48280	1.000	-1.7975	1.5455
	302.00	-1.07750	.48280	.384	-2.7490	.5940
	303.00	-.72703	.48280	.794	-2.3985	.9445
302.00	239.00	-.79421	.48280	.719	-2.4657	.8773
	240.00	-.32145	.48280	.997	-1.9930	1.3501
	242.00	-.19635	.48280	1.000	-1.8679	1.4752
	248.00	1.07228	.48280	.389	-.5992	2.7438
	267.00	.95148	.48280	.528	-.7200	2.6230
	271.00	1.07750	.48280	.384	-.5940	2.7490
	303.00	.35047	.48280	.995	-1.3210	2.0220
303.00	239.00	-1.14468	.48280	.317	-2.8162	.5268
	240.00	-.67192	.48280	.848	-2.3434	.9996
	242.00	-.54682	.48280	.940	-2.2183	1.1247
	248.00	.72180	.48280	.799	-.9497	2.3933
	267.00	.60101	.48280	.906	-1.0705	2.2725
	271.00	.72703	.48280	.794	-.9445	2.3985
	302.00	-.35047	.48280	.995	-2.0220	1.3210

*. The mean difference is significant at the 0.05 level.

LNbasalarea

Tukey HSD[a]

		Subset for alpha = 0.05	
Origin	N	1	2
271.00	3	-4.1381	
248.00	3	-4.1329	
267.00	3	-4.0121	
303.00	3	-3.4111	-3.4111
302.00	3	-3.0606	-3.0606
242.00	3	-2.8642	-2.8642
240.00	3	-2.7391	-2.7391
239.00	3		-2.2664
Sig.		.138	.317

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 3.000.

For height the data for one origin was (very highly) significantly different from normal (also when LN transformed) but variances were heterogeneous so a Kruskal Wallis test was used. Survival and stems were not normally distributed so a Kruskal Wallis test was also used to este for significant differences.

Table of rankings has been omitted because of the large amount of data.

Test Statistics[a,b]

	Height	Survival	Stems
Chi-Square	14.700	6.458	11.212
df	7	7	7
Asymp. Sig.	**.040**	.487	.130

a. Kruskal Wallis Test
b. Grouping Variable: Origin

Only for height was there a significant difference between origins. To identify where the differences lay between origins Mann Whitney tests were performed. The p values for the pairwise comparisons of origins are shown below for all pairs in addition to the median height for each origin.

Median height (m)		6.0	8.1	9.9	11.2	11.3	12.3	14.3	18.7
		248	271	267	242	303	240	239	302
6.0	248		0.507	0.513	0.275	0.275	0.275	**0.050**	**0.050**
8.1	271			0.507	0.121	0.121	**0.046**	**0.046**	**0.046**
9.9	267				0.275	0.275	**0.050**	**0.050**	**0.050**
11.2	242					0.827	0.513	0.275	0.127
11.3	303						0.513	0.127	0.127
12.3	240							0.127	0.127
14.3	239								0.827
18.7	302								

Appendix 4.6 Torridge, comparison of best survival origins by block

Tests of Normality

	Block	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	Df	Sig.
Height	1.00	.195	8	.200*	.920	8	.427
	2.00	.216	8	.200*	.886	8	.214
	3.00	.261	8	.117	.854	8	.104
Basalarea	1.00	.331	8	.010	.769	8	.013
	2.00	.240	8	.193	.858	8	.114
	3.00	.256	8	.132	.872	8	.159
LNbasalarea	1.00	.181	8	.200*	.908	8	.341
	2.00	.206	8	.200*	.954	8	.752
	3.00	.227	8	.200*	.904	8	.312
Survival	1.00	.208	8	.200*	.926	8	.482
	2.00	.154	8	.200*	.972	8	.915
	3.00	.323	8	.014	.792	8	.024
Arcsinsvvl	1.00	.232	8	.200*	.914	8	.383
	2.00	.235	8	.200*	.910	8	.354
	3.00	.340	8	.007	.768	8	.013
Stems	1.00	.236	8	.200*	.887	8	.218
	2.00	.196	8	.200*	.886	8	.213
	3.00	.238	8	.200*	.878	8	.180
LNheight	1.00	.217	8	.200*	.896	8	.266
	2.00	.162	8	.200*	.927	8	.486
	3.00	.187	8	.200*	.940	8	.609

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
LNbasalarea	2.732	2	21	.088
Height	.095	2	21	.910
Basalarea	2.433	2	21	.112
Survival	.583	2	21	.567
Arcsinsvvl	.659	2	21	.528
Stems	2.229	2	21	.133
LNheight	.342	2	21	.715

The height, LN basal area and stems data were normally distributed and variances were equal so an ANOVA was applied.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LNbasalarea	Between Groups	.480	2	.240	.321	.729
	Within Groups	15.732	21	.749		
	Total	16.212	23			
Height	Between Groups	17.378	2	8.689	.413	.667
	Within Groups	442.207	21	21.057		
	Total	459.585	23			
Stems	Between Groups	.109	2	.055	.730	.494
	Within Groups	1.572	21	.075		
	Total	1.681	23			

For survival, the data was not normal in one block and so a non parametric Kruskal Wallis test was performed:

Ranks

	Block	N	Mean Rank
Survival	1.00	8	12.75
	2.00	8	12.44
	3.00	8	12.31
	Total	24	

Test Statistics[a,b]

	Survival
Chi-Square	.017
df	2
Asymp. Sig.	.992

a. Kruskal Wallis Test
b. Grouping Variable: Block

No significant differences were found between blocks.

Appendix 4.7 Chiddingfold, comparison of best survival origins by origin

Tests of Normality

	Origin	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Height	241.00	.329	3	.	.868	3	.290
	243.00	.371	3	.	.785	3	.079
	248.00	.302	3	.	.910	3	.418
	273.00	.321	3	.	.881	3	.328
	278.00	.230	3	.	.981	3	.736
	281.00	.358	3	.	.812	3	.144
	283.00	.374	3	.	.778	3	.062
	287.00	.340	3	.	.848	3	.235
	288.00	.380	3	.	.761	3	.025
	289.00	.287	3	.	.930	3	.488
	291.00	.197	3	.	.996	3	.873
	294.00	.286	3	.	.930	3	.490
	302.00	.184	3	.	.999	3	.927
	303.00	.301	3	.	.912	3	.424
BArea	241.00	.225	3	.	.984	3	.759
	243.00	.334	3	.	.859	3	.265
	248.00	.319	3	.	.886	3	.341
	273.00	.239	3	.	.975	3	.699
	278.00	.297	3	.	.916	3	.440
	281.00	.178	3	.	.999	3	.954
	283.00	.213	3	.	.990	3	.807
	287.00	.240	3	.	.974	3	.692
	288.00	.340	3	.	.850	3	.239
	289.00	.188	3	.	.998	3	.913
	291.00	.343	3	.	.843	3	.222
	294.00	.306	3	.	.905	3	.400
	302.00	.333	3	.	.862	3	.272
	303.00	.291	3	.	.925	3	.470
LNBA	241.00	.269	3	.	.950	3	.569
	243.00	.356	3	.	.817	3	.155
	248.00	.276	3	.	.942	3	.536
	273.00	.186	3	.	.998	3	.918
	278.00	.276	3	.	.942	3	.536
	281.00	.210	3	.	.991	3	.820
	283.00	.207	3	.	.992	3	.832
	287.00	.222	3	.	.985	3	.768
	288.00	.280	3	.	.937	3	.517
	289.00	.235	3	.	.978	3	.716
	291.00	.363	3	.	.802	3	.119
	294.00	.242	3	.	.973	3	.683
	302.00	.337	3	.	.853	3	.250
	303.00	.252	3	.	.965	3	.642
Survival	241.00	.385	3	.	.750	3	.000
	243.00	.175	3	.	1.000	3	1.000
	248.00	.175	3	.	1.000	3	1.000
	273.00	.175	3	.	1.000	3	1.000
	278.00	.175	3	.	1.000	3	1.000
	281.00	.276	3	.	.942	3	.537
	283.00	.292	3	.	.923	3	.463
	287.00	.253	3	.	.964	3	.637
	288.00	.204	3	.	.993	3	.843
	289.00	.385	3	.	.750	3	.000
	291.00	.219	3	.	.987	3	.780
	294.00	.219	3	.	.987	3	.780

	302.00	.253	3	.	.964	3	.637
	303.00	.385	3	.	.750	3	.000
Arcsinsvl	241.00	.385	3	.	.750	3	.000
	243.00	.175	3	.	1.000	3	.999
	248.00	.175	3	.	1.000	3	1.000
	273.00	.176	3	.	1.000	3	.981
	278.00	.175	3	.	1.000	3	1.000
	281.00	.279	3	.	.939	3	.525
	283.00	.290	3	.	.925	3	.472
	287.00	.240	3	.	.974	3	.691
	288.00	.187	3	.	.998	3	.917
	289.00	.385	3	.	.750	3	.000
	291.00	.224	3	.	.984	3	.760
	294.00	.241	3	.	.974	3	.690
	302.00	.314	3	.	.892	3	.361
	303.00	.385	3	.	.750	3	.000
Stems	241.00	.318	3	.	.887	3	.344
	243.00	.312	3	.	.895	3	.370
	248.00	.337	3	.	.855	3	.253
	273.00	.328	3	.	.871	3	.298
	278.00	.264	3	.	.954	3	.588
	281.00	.291	3	.	.925	3	.471
	283.00	.385	3	.	.750	3	.000
	287.00	.185	3	.	.998	3	.923
	288.00	.293	3	.	.922	3	.459
	289.00	.238	3	.	.976	3	.702
	291.00	.385	3	.	.750	3	.000
	294.00	.360	3	.	.809	3	.136
	302.00	.273	3	.	.945	3	.549
	303.00	.385	3	.	.750	3	.000
LNheight	241.00	.336	3	.	.856	3	.255
	243.00	.365	3	.	.797	3	.108
	248.00	.362	3	.	.804	3	.125
	273.00	.330	3	.	.866	3	.285
	278.00	.246	3	.	.970	3	.667
	281.00	.360	3	.	.808	3	.133
	283.00	.376	3	.	.772	3	.050
	287.00	.346	3	.	.837	3	.206
	288.00	.379	3	.	.764	3	.032
	289.00	.301	3	.	.911	3	.422
	291.00	.226	3	.	.983	3	.753
	294.00	.304	3	.	.907	3	.409
	302.00	.203	3	.	.994	3	.848
	303.00	.311	3	.	.898	3	.379

a. Lilliefors Significance Correction

Basal area, LN basal area and height (other than origin 288) are normally distributed so test for equality of variances:

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Height	3.140	13	28	.005
BArea	3.735	13	28	.002
LNBA	2.029	13	28	.057
Survival	.844	13	28	.615
Arcsinsvl	.959	13	28	.511
Stems	3.514	13	28	.003
LNheight	10.912	13	28	.000

Variances for LN basal area were not significantly different so an ANOVA was conducted which showed significant differences so was followed by a post hoc

Tukey's test. For height, stems and survival a non parametric Kruskal Wallis was used.

ANOVA

LNBA

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	10.182	13	.783	2.856	**.010**
Within Groups	7.678	28	.274		
Total	17.860	41			

Multiple Comparisons

Dependent Variable: LNBA
Tukey HSD

(I) Origin	(J) Origin	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
241.00	243.00	-.29269	.42756	1.000	-1.8577	1.2723
	248.00	-.08441	.42756	1.000	-1.6494	1.4806
	273.00	-.04174	.42756	1.000	-1.6068	1.5233
	278.00	.82575	.42756	.794	-.7393	2.3908
	281.00	1.34331	.42756	.150	-.2217	2.9083
	283.00	.41681	.42756	.999	-1.1482	1.9818
	287.00	1.00234	.42756	.539	-.5627	2.5674
	288.00	.39165	.42756	.999	-1.1734	1.9567
	289.00	.65370	.42756	.950	-.9113	2.2187
	291.00	-.09483	.42756	1.000	-1.6599	1.4702
	294.00	.73053	.42756	.896	-.8345	2.2956
	302.00	-.29973	.42756	1.000	-1.8648	1.2653
	303.00	.22516	.42756	1.000	-1.3399	1.7902
243.00	241.00	.29269	.42756	1.000	-1.2723	1.8577
	248.00	.20828	.42756	1.000	-1.3568	1.7733
	273.00	.25095	.42756	1.000	-1.3141	1.8160
	278.00	1.11844	.42756	.374	-.4466	2.6835
	281.00	1.63600*	.42756	**.034**	.0710	3.2010
	283.00	.70950	.42756	.913	-.8555	2.2745
	287.00	1.29503	.42756	.186	-.2700	2.8601
	288.00	.68434	.42756	.932	-.8807	2.2494
	289.00	.94639	.42756	.624	-.6186	2.5114
	291.00	.19786	.42756	1.000	-1.3672	1.7629
	294.00	1.02322	.42756	.508	-.5418	2.5883
	302.00	-.00704	.42756	1.000	-1.5721	1.5580
	303.00	.51785	.42756	.992	-1.0472	2.0829
248.00	241.00	.08441	.42756	1.000	-1.4806	1.6494
	243.00	-.20828	.42756	1.000	-1.7733	1.3568
	273.00	.04267	.42756	1.000	-1.5224	1.6077
	278.00	.91016	.42756	.677	-.6549	2.4752
	281.00	1.42772	.42756	.101	-.1373	2.9928
	283.00	.50122	.42756	.994	-1.0638	2.0663
	287.00	1.08675	.42756	.417	-.4783	2.6518
	288.00	.47606	.42756	.996	-1.0890	2.0411
	289.00	.73812	.42756	.889	-.8269	2.3032
	291.00	-.01042	.42756	1.000	-1.5755	1.5546
	294.00	.81494	.42756	.807	-.7501	2.3800
	302.00	-.21531	.42756	1.000	-1.7804	1.3497
	303.00	.30957	.42756	1.000	-1.2555	1.8746
273.00	241.00	.04174	.42756	1.000	-1.5233	1.6068
	243.00	-.25095	.42756	1.000	-1.8160	1.3141
	248.00	-.04267	.42756	1.000	-1.6077	1.5224
	278.00	.86749	.42756	.738	-.6975	2.4325

	281.00	1.38505	.42756	.124	-.1800	2.9501
	283.00	.45855	.42756	.997	-1.1065	2.0236
	287.00	1.04408	.42756	.477	-.5210	2.6091
	288.00	.43339	.42756	.999	-1.1316	1.9984
	289.00	.69544	.42756	.924	-.8696	2.2605
	291.00	-.05309	.42756	1.000	-1.6181	1.5119
	294.00	.77227	.42756	.856	-.7928	2.3373
	302.00	-.25798	.42756	1.000	-1.8230	1.3071
	303.00	.26690	.42756	1.000	-1.2981	1.8319
278.00	241.00	-.82575	.42756	.794	-2.3908	.7393
	243.00	-1.11844	.42756	.374	-2.6835	.4466
	248.00	-.91016	.42756	.677	-2.4752	.6549
	273.00	-.86749	.42756	.738	-2.4325	.6975
	281.00	.51756	.42756	.992	-1.0475	2.0826
	283.00	-.40894	.42756	.999	-1.9740	1.1561
	287.00	.17659	.42756	1.000	-1.3884	1.7416
	288.00	-.43411	.42756	.999	-1.9991	1.1309
	289.00	-.17205	.42756	1.000	-1.7371	1.3930
	291.00	-.92058	.42756	.662	-2.4856	.6445
	294.00	-.09522	.42756	1.000	-1.6603	1.4698
	302.00	-1.12548	.42756	.365	-2.6905	.4396
	303.00	-.60059	.42756	.973	-2.1656	.9644
281.00	241.00	-1.34331	.42756	.150	-2.9083	.2217
	243.00	-1.63600*	.42756	**<u>.034</u>**	-3.2010	-.0710
	248.00	-1.42772	.42756	.101	-2.9928	.1373
	273.00	-1.38505	.42756	.124	-2.9501	.1800
	278.00	-.51756	.42756	.992	-2.0826	1.0475
	283.00	-.92650	.42756	.653	-2.4915	.6385
	287.00	-.34097	.42756	1.000	-1.9060	1.2241
	288.00	-.95167	.42756	.616	-2.5167	.6134
	289.00	-.68961	.42756	.928	-2.2546	.8754
	291.00	-1.43814	.42756	.096	-3.0032	.1269
	294.00	-.61278	.42756	.969	-2.1778	.9523
	302.00	-1.64304*	.42756	**<u>.033</u>**	-3.2081	-.0780
	303.00	-1.11815	.42756	.375	-2.6832	.4469
283.00	241.00	-.41681	.42756	.999	-1.9818	1.1482
	243.00	-.70950	.42756	.913	-2.2745	.8555
	248.00	-.50122	.42756	.994	-2.0663	1.0638
	273.00	-.45855	.42756	.997	-2.0236	1.1065
	278.00	.40894	.42756	.999	-1.1561	1.9740
	281.00	.92650	.42756	.653	-.6385	2.4915
	287.00	.58553	.42756	.978	-.9795	2.1506
	288.00	-.02516	.42756	1.000	-1.5902	1.5399
	289.00	.23689	.42756	1.000	-1.3281	1.8019
	291.00	-.51164	.42756	.993	-2.0767	1.0534
	294.00	.31372	.42756	1.000	-1.2513	1.8788
	302.00	-.71653	.42756	.908	-2.2816	.8485
	303.00	-.19165	.42756	1.000	-1.7567	1.3734
287.00	241.00	-1.00234	.42756	.539	-2.5674	.5627
	243.00	-1.29503	.42756	.186	-2.8601	.2700
	248.00	-1.08675	.42756	.417	-2.6518	.4783
	273.00	-1.04408	.42756	.477	-2.6091	.5210
	278.00	-.17659	.42756	1.000	-1.7416	1.3884
	281.00	.34097	.42756	1.000	-1.2241	1.9060
	283.00	-.58553	.42756	.978	-2.1506	.9795
	288.00	-.61070	.42756	.970	-2.1757	.9543
	289.00	-.34864	.42756	1.000	-1.9137	1.2164
	291.00	-1.09717	.42756	.403	-2.6622	.4679
	294.00	-.27181	.42756	1.000	-1.8369	1.2932
	302.00	-1.30207	.42756	.181	-2.8671	.2630
	303.00	-.77718	.42756	.850	-2.3422	.7879

288.00	241.00	-.39165	.42756	.999	-1.9567	1.1734
	243.00	-.68434	.42756	.932	-2.2494	.8807
	248.00	-.47606	.42756	.996	-2.0411	1.0890
	273.00	-.43339	.42756	.999	-1.9984	1.1316
	278.00	.43411	.42756	.999	-1.1309	1.9991
	281.00	.95167	.42756	.616	-.6134	2.5167
	283.00	.02516	.42756	1.000	-1.5399	1.5902
	287.00	.61070	.42756	.970	-.9543	2.1757
	289.00	.26206	.42756	1.000	-1.3030	1.8271
	291.00	-.48648	.42756	.996	-2.0515	1.0786
	294.00	.33888	.42756	1.000	-1.2262	1.9039
	302.00	-.69137	.42756	.927	-2.2564	.8737
	303.00	-.16649	.42756	1.000	-1.7315	1.3985
289.00	241.00	-.65370	.42756	.950	-2.2187	.9113
	243.00	-.94639	.42756	.624	-2.5114	.6186
	248.00	-.73812	.42756	.889	-2.3032	.8269
	273.00	-.69544	.42756	.924	-2.2605	.8696
	278.00	.17205	.42756	1.000	-1.3930	1.7371
	281.00	.68961	.42756	.928	-.8754	2.2546
	283.00	-.23689	.42756	1.000	-1.8019	1.3281
	287.00	.34864	.42756	1.000	-1.2164	1.9137
	288.00	-.26206	.42756	1.000	-1.8271	1.3030
	291.00	-.74853	.42756	.879	-2.3136	.8165
	294.00	.07682	.42756	1.000	-1.4882	1.6419
	302.00	-.95343	.42756	.613	-2.5185	.6116
	303.00	-.42855	.42756	.999	-1.9936	1.1365
291.00	241.00	.09483	.42756	1.000	-1.4702	1.6599
	243.00	-.19786	.42756	1.000	-1.7629	1.3672
	248.00	.01042	.42756	1.000	-1.5546	1.5755
	273.00	.05309	.42756	1.000	-1.5119	1.6181
	278.00	.92058	.42756	.662	-.6445	2.4856
	281.00	1.43814	.42756	.096	-.1269	3.0032
	283.00	.51164	.42756	.993	-1.0534	2.0767
	287.00	1.09717	.42756	.403	-.4679	2.6622
	288.00	.48648	.42756	.996	-1.0786	2.0515
	289.00	.74853	.42756	.879	-.8165	2.3136
	294.00	.82536	.42756	.794	-.7397	2.3904
	302.00	-.20489	.42756	1.000	-1.7699	1.3601
	303.00	.31999	.42756	1.000	-1.2451	1.8850
294.00	241.00	-.73053	.42756	.896	-2.2956	.8345
	243.00	-1.02322	.42756	.508	-2.5883	.5418
	248.00	-.81494	.42756	.807	-2.3800	.7501
	273.00	-.77227	.42756	.856	-2.3373	.7928
	278.00	.09522	.42756	1.000	-1.4698	1.6603
	281.00	.61278	.42756	.969	-.9523	2.1778
	283.00	-.31372	.42756	1.000	-1.8788	1.2513
	287.00	.27181	.42756	1.000	-1.2932	1.8369
	288.00	-.33888	.42756	1.000	-1.9039	1.2262
	289.00	-.07682	.42756	1.000	-1.6419	1.4882
	291.00	-.82536	.42756	.794	-2.3904	.7397
	302.00	-1.03025	.42756	.498	-2.5953	.5348
	303.00	-.50537	.42756	.994	-2.0704	1.0597
302.00	241.00	.29973	.42756	1.000	-1.2653	1.8648
	243.00	.00704	.42756	1.000	-1.5580	1.5721
	248.00	.21531	.42756	1.000	-1.3497	1.7804
	273.00	.25798	.42756	1.000	-1.3071	1.8230
	278.00	1.12548	.42756	.365	-.4396	2.6905
	281.00	1.64304*	.42756	**.033**	.0780	3.2081
	283.00	.71653	.42756	.908	-.8485	2.2816
	287.00	1.30207	.42756	.181	-.2630	2.8671
	288.00	.69137	.42756	.927	-.8737	2.2564

	289.00	.95343	.42756	.613	-.6116	2.5185
	291.00	.20489	.42756	1.000	-1.3601	1.7699
	294.00	1.03025	.42756	.498	-.5348	2.5953
	303.00	.52488	.42756	.991	-1.0402	2.0899
303.00	241.00	-.22516	.42756	1.000	-1.7902	1.3399
	243.00	-.51785	.42756	.992	-2.0829	1.0472
	248.00	-.30957	.42756	1.000	-1.8746	1.2555
	273.00	-.26690	.42756	1.000	-1.8319	1.2981
	278.00	.60059	.42756	.973	-.9644	2.1656
	281.00	1.11815	.42756	.375	-.4469	2.6832
	283.00	.19165	.42756	1.000	-1.3734	1.7567
	287.00	.77718	.42756	.850	-.7879	2.3422
	288.00	.16649	.42756	1.000	-1.3985	1.7315
	289.00	.42855	.42756	.999	-1.1365	1.9936
	291.00	-.31999	.42756	1.000	-1.8850	1.2451
	294.00	.50537	.42756	.994	-1.0597	2.0704
	302.00	-.52488	.42756	.991	-2.0899	1.0402

*. The mean difference is significant at the 0.05 level.

LNBA

Tukey HSD[a]

Origin	N	Subset for alpha = 0.05 1	2
281.00	3	-4.7522	
287.00	3	-4.4112	-4.4112
278.00	3	-4.2346	-4.2346
294.00	3	-4.1394	-4.1394
289.00	3	-4.0626	-4.0626
283.00	3	-3.8257	-3.8257
288.00	3	-3.8005	-3.8005
303.00	3	-3.6340	-3.6340
241.00	3	-3.4089	-3.4089
273.00	3	-3.3671	-3.3671
248.00	3	-3.3245	-3.3245
291.00	3	-3.3140	-3.3140
243.00	3		-3.1162
302.00	3		-3.1092
Sig.		.096	.181

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 3.000.

Significant differences in LN basal area were found between 281 and 243 and also 281 and 303.

The Kruskal Wallis test for height, stems and survival is shown below:

Test Statistics[a,b]

	Height	Survival	Stems
Chi-Square	17.810	6.971	28.620
df	13	13	13
Asymp. Sig.	.165	.904	**.007**

a. Kruskal Wallis Test
b. Grouping Variable: Origin

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Only for number of stems was there a significant difference between origins. To identify where the differences lay between origins Mann Whitney tests were performed. The p values for the pairwise comparisons of origins are shown below for all pairs in addition to the median number of stems for each origin.

Median stem number		1	1	1.125	1.33	1.43	1.5	1.5	1.67	1.8	1.8	1.8	2	2	2
		283	303	302	289	243	281	294	241	287	278	273	288	248	291
1	283		0.796	0.487	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.043**
1	303			0.637	0.507	0.121	0.121	**0.046**	0.121	**0.046**	**0.046**	**0.046**	**0.046**	**0.046**	**0.043**
1.125	302				0.513	0.127	0.121	**0.05**	0.127	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.046**
1.33	289					0.512	0.184	**0.05**	0.184	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.046**
1.43	243						0.827	0.513	0.827	0.513	0.513	0.513	0.275	0.275	0.507
1.5	281						-	0.513	1	0.376	0.376	0.658	0.184	0.184	0.105
1.5	294								0.827	0.513	0.513	0.658	0.275	0.275	0.268
1.67	241									0.275	0.127	0.275	0.184	**0.05**	**0.046**
1.8	287										0.822	0.658	0.376	0.184	0.105
1.8	278											0.658	0.658	0.184	0.105
1.8	273												0.275	**0.05**	**0.046**
2	288													1	0.817
2	248														0.817
2	291														

Appendix 4.8 Comparison of best survival origins by block

Tests of Normality

	Block	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Height	1.00	.117	59	.044	.911	59	.000
	2.00	.105	57	.186	.964	57	.089
	3.00	.074	65	.200*	.977	65	.280
Basalarea	1.00	.125	59	.023	.917	59	.001
	2.00	.187	57	.000	.720	57	.000
	3.00	.177	65	.000	.883	65	.000
Survival	1.00	.119	59	.038	.958	59	.040
	2.00	.180	57	.000	.855	57	.000
	3.00	.143	65	.002	.954	65	.017
Stems	1.00	.155	59	.001	.885	59	.000
	2.00	.224	57	.000	.824	57	.000
	3.00	.201	65	.000	.682	65	.000
LNheight	1.00	.242	59	.000	.522	59	.000
	2.00	.210	57	.000	.695	57	.000
	3.00	.105	65	.071	.946	65	.007
LNbasalarea	1.00	.081	59	.200*	.962	59	.065
	2.00	.110	57	.084	.945	57	.012
	3.00	.101	65	.096	.946	65	.007
Arcsinsvvl	1.00	.107	59	.092	.965	59	.083
	2.00	.165	57	.001	.832	57	.000
	3.00	.161	65	.000	.956	65	.022
LNStems	1.00	.103	59	.184	.945	59	.010
	2.00	.256	57	.000	.853	57	.000
	3.00	.129	65	.009	.890	65	.000

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

None of the variables were normally distributed before or after transformation so a Kruskal Wallis test was used:

Ranks

	Block	N	Mean Rank
Height	1.00	59	102.88
	2.00	57	92.92
	3.00	65	78.53
	Total	181	
Basalarea	1.00	60	95.33
	2.00	57	99.07
	3.00	65	81.32
	Total	182	
Survival	1.00	66	111.84
	2.00	66	70.05
	3.00	66	116.61
	Total	198	
Stems	1.00	62	96.28
	2.00	58	88.81
	3.00	65	93.61
	Total	185	

Test Statistics[a,b]

	Height	Basalarea	Survival	Stems
Chi-Square	6.794	3.920	26.837	.611
df	2	2	2	2
Asymp. Sig.	**.033**	.141	**.000**	.737

a. Kruskal Wallis Test

b. Grouping Variable: Block

Significant differences were detected in height and survival by block.

Appendix 4.9 Basal area ranking of origins across the tree trials.

There were more than 63 origins and SPSS cannot test heterogeneity of variances for more than 50 origins. As such it was not possible to check this assumption that underpins the use of ANOVA. To test differences across all origins, a non parametic approach (Kruskal Wallis) was adopted that did not require normality or equality of variances.

origin	N	Mean Rank
221.00	3	43.83
302.00	9	71.06
188.00	2	74.00
243.00	7	95.14
216.00	6	108.25
239.00	9	118.22
241.00	6	128.33
240.00	9	136.44
296.00	8	139.38
272.00	8	141.38
303.00	9	142.22
242.00	7	143.71
273.00	9	148.33
261.00	6	154.50
256.00	7	161.71
246.00	9	167.83
245.00	5	169.00
254.00	9	171.22
214.00	6	172.75
280.00	8	181.19
279.00	8	183.44
251.00	6	189.50
253.00	8	190.75
215.00	9	193.17
283.00	8	196.19
286.00	7	200.14
265.00	7	211.93
292.00	8	225.19
277.00	9	226.67
252.00	8	227.75
248.00	9	227.89
255.00	6	243.67
250.00	7	245.71
291.00	8	246.56
271.00	9	247.11

282.00	7	249.50
295.00	6	266.17
293.00	9	269.78
288.00	9	270.28
249.00	9	272.06
264.00	7	275.29
290.00	8	281.31
266.00	8	281.50
284.00	7	283.43
270.00	8	288.63
267.00	9	289.00
278.00	9	293.94
263.00	7	303.93
289.00	8	306.69
268.00	3	313.00
262.00	8	316.19
247.00	7	321.64
285.00	9	335.50
269.00	7	336.57
281.00	7	338.00
258.00	5	338.60
294.00	8	345.75
276.00	9	347.94
274.00	8	370.38
257.00	6	373.08
287.00	7	379.21
275.00	8	381.63
260.00	9	390.28
259.00	7	397.71
Total	478	

Test Statistics[a,b]

	BArank
Chi-Square	180.119
df	63
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Origin

There were very highly significant differences in basal area by origin across the three trials.

Appendix 5 Origins tested at Exeter

Appendix 5.1 Details of origins of species other than *E. delegatensis*

(Forestry Commission no date and Evans 1983)

Species	Alice Holt number	Locality	Altitude (m)
E. nitens	45	Plot 209, Kilmun, Argyll, Scotland	
E. nitens	56	Barnewall Plain, Rubicon area, Victoria	1170
E. nitens	57	Macalister, Connors Plain, Victoria	1260
E. nitens	58	Macalister, Mt Wellington, Victoria	1280
E. nitens	87	Barrington Tops, NSW	1520
E. nitens	88	Barren Mt, NSW	1460
E. nitens	89	Point Lookout, NSW	1500
E. nitens	90	Badja Mt, NSW	1250
E. nitens	91	Tallaganda State Forest, NSW	1200
E. nitens	92	Anembo Trig, NSW	1400
E. nitens	94	Mount St Gwinear, Victoria	1175
E. nitens	95	Macalister, Connors Plain, Victoria	1310
E. nitens	97	Mount Torbreck, Rubicon, Victoria	1220
E. dalrympleana	169	Laura Gap, ACT	1320
E. dalrympleana	170	Smokers Flat, ACT	1400
E. johnstonii	37[1]	Kirroughtree Forest S, Scotland	
E. johnstonii	69[2]	Misery Plateau, Tasmania	747
E. johnstonii	121	Hartz Mountains, Tasmania (Tree 1)	800
E. johnstonii	122	Hartz Mountains, Tasmania (Tree 2)	800
E. johnstonii	123	Hartz Mountains, Tasmania (Tree 3)	760

E. johnstonii	124	Hartz Mountains, Tasmania (Tree 4)	760
E. johnstonii	125	Hartz Mountains, Tasmania (Tree 5)	760
E. nitida	21	Arthur's Lake, Tasmania	1000
E. nitida	23[3]	Breona, Tasmania	1000
E. nitida	24	Kernow, St Clements, Cornwall, England	900
E. nitida	48	Mt Field W of Lake Dobson, Tasmania	1200-1300
E. nitida	134	Hartz Mountains, Tasmania	800
E. nitida	135	Lake Mackenzie, Tasmania (tree 1)	1100
E. nitida	136	Lake Mackenzie, Tasmania (tree 2)	1100
E. nitida	137	Lake Mackenzie, Tasmania (tree 3)	1100
E. subcrenulata	115	Mount Cattley, Tasmania (Tree 1)	720
E. subcrenulata	116	Mount Cattley, Tasmania (Tree 2)	720
E. subcrenulata	117	Mount Cattley, Tasmania (Tree 3)	720
E. subcrenulata	118	Mount Cattley, Tasmania (Tree 4)	720
E. subcrenulata	119	Mount Cattley, Tasmania (Tree 5)	720

During the beat-up in 1982 the following replacements of origins were made:

1. *E. johnstonii* 37 was replaced with 229, originating from the north end of Florentine Valley, Tasmania (altitude 1000m)
2. *E. johnstonii* 69 was replaced with *E. subcrenulata* 171 from east of Great Lake, Tasmania (altitude 1100-1200 m)
3. *E. nitida* 23 was replaced with *E. nitida*, Mount Wellington summit (altitude 1200 m)

Appendix 5.2 Details of origins of *E. delegatensis*

(Forestry Commission no date)

Species	Alice Holt number	Locality	Altitude
E. delegatensis	30	Hunterston, Tasmania	762
E. delegatensis	131	Ben Lomond, Tasmania	1200
E. delegatensis	132	Mount Barrow, Tasmania	1000
E. delegatensis	133	Steppes, Tasmania	900
E. delegatensis	148[1]	Yaouk Hill Range, NSW	1340
E. delegatensis	149	Laura Gap, ACT	1350
E. delegatensis	150	Mount Bogong, NSW	1525
E. delegatensis	151	The Pinnacle, NSW	1500
E. delegatensis	152	Mount Buffalo, Victoria	1350
E. delegatensis	153	Lake Mountain Victoria	1310
E. delegatensis	154	Ben Lomond, Tasmania	1220
E. delegatensis	155	Miena, Tasmania	960
E. delegatensis	156	Mount Dromedary, Tasmania	800
E. delegatensis	157	Forlorn Hope Track, Victoria	1400
E. delegatensis	158	Ben Lomond, Tasmania	1200

Origin 148 was replaced a year after the initial planting because of complete failure with origin 228, East of Great Lake, Tasmania, altitude 1100 m.

Appendix 6 Statistical supporting data for Exeter Trial.

Appendix 6.1 Linear regressions for survival, height, basal area against altitude

E. nitida/ E. coccifera (all origins) linear regression with altitude

Survival

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.092[a]	.008	-.157	.10794

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.001	1	.001	.051	.829[b]
	Residual	.070	6	.012		
	Total	.071	7			

a. Dependent Variable: Survival
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.084	.326		.257	.805
	Altitude	6.776E-5	.000	.092	.226	.829

a. Dependent Variable: Survival

Height

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.412[a]	.170	.004	2.77684

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	7.894	1	7.894	1.024	.358[b]
	Residual	38.554	5	7.711		
	Total	46.449	6			

a. Dependent Variable: Height
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	12.156	9.477		1.283	.256
	Altitude	.009	.009	.412	1.012	.358

a. Dependent Variable: Height

Basal area

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.703[a]	.495	.394	.07720

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.029	1	.029	4.895	.078[b]
	Residual	.030	5	.006		
	Total	.059	6			

a. Dependent Variable: Basalarea
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.392	.263		-1.487	.197
	Altitude	.001	.000	.703	2.213	.078

a. Dependent Variable: Basalarea

E. coccifera origins

Survival

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.408[a]	.166	-.042	.11057

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.010	1	.010	.797	.423[b]
	Residual	.049	4	.012		
	Total	.059	5			

a. Dependent Variable: Survival
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.743	.634		1.172	.306
	Altitude	-.001	.001	-.408	-.892	.423

a. Dependent Variable: Survival

Height

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate

1	.152[a]	.023	-.302	3.44940

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.845	1	.845	.071	.807[b]
	Residual	35.695	3	11.898		
	Total	36.540	4			

a. Dependent Variable: Height
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	15.250	26.874		.567	.610
	Altitude	.007	.024	.152	.266	.807

a. Dependent Variable: Height

Basal area

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.694[a]	.481	.308	.05589

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.009	1	.009	2.780	.194[b]
	Residual	.009	3	.003		
	Total	.018	4			

a. Dependent Variable: Basalarea
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.489	.435		-1.124	.343
	Altitude	.001	.000	.694	1.667	.194

a. Dependent Variable: Basalarea

E. delegatensis (all origins) regression with altitude

Survival

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.164[a]	.027	-.048	.13929

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.007	1	.007	.359	.559[b]
	Residual	.252	13	.019		
	Total	.259	14			

a. Dependent Variable: Survival
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.017	.181		.093	.928
	Altitude	9.018E-5	.000	.164	.599	.559

a. Dependent Variable: Survival

Height

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.132[a]	.017	-.105	1.86710

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.493	1	.493	.141	.717[b]
	Residual	27.888	8	3.486		
	Total	28.381	9			

a. Dependent Variable: Height
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	18.923	3.631		5.212	.001
	Altitude	.001	.003	.132	.376	.717

a. Dependent Variable: Height

Basal area

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.019[a]	.000	-.125	.21526

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.000	1	.000	.003	.958[b]
	Residual	.371	8	.046		
	Total	.371	9			

a. Dependent Variable: Basalarea
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.342	.419		.816	.438
	Altitude	-1.873E-5	.000	-.019	-.055	.958

a. Dependent Variable: Basalarea

E. delegatensis (Tasmania) regression with altitude

Survival

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.483[a]	.234	.106	.15076

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.042	1	.042	1.830	.225[b]
	Residual	.136	6	.023		
	Total	.178	7			

a. Dependent Variable: Survival
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.316	.334		-.947	.380
	Altitude	.000	.000	.483	1.353	.225

a. Dependent Variable: Survival

Height

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.363[a]	.132	-.158	2.57623

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.017	1	3.017	.455	.548[b]
	Residual	19.911	3	6.637		
	Total	22.928	4			

a. Dependent Variable: Height
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	27.323	11.246		2.429	.093
	Altitude	-.007	.011	-.363	-.674	.548

a. Dependent Variable: Height

Basal area

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.908[a]	.824	.766	.11600

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.189	1	.189	14.063	.033[b]
	Residual	.040	3	.013		
	Total	.230	4			

a. Dependent Variable: Basalarea
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.508	.506		-2.979	.059
	Altitude	.002	.000	.908	3.750	.033

a. Dependent Variable: Basalarea

E. delegatensis (Mainland) regression with altitude

Survival

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.078[a]	.006	-.193	.12655

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.000	1	.000	.031	.867[b]
	Residual	.080	5	.016		
	Total	.081	6			

a. Dependent Variable: Survival
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.035	.861		-.041	.969
	Altitude	.000	.001	.078	.176	.867

a. Dependent Variable: Survival

Height

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.034[a]	.001	-.332	1.00805

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.003	1	.003	.003	.957[b]
	Residual	3.049	3	1.016		
	Total	3.052	4			

a. Dependent Variable: Height
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	21.243	8.254		2.574	.082
	Altitude	.000	.006	-.034	-.059	.957

a. Dependent Variable: Height

Basal area

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.044[a]	.002	-.331	.18555

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.000	1	.000	.006	.944[b]
	Residual	.103	3	.034		
	Total	.103	4			

a. Dependent Variable: Basalarea
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.373	1.519		.245	.822
	Altitude	-8.324E-5	.001	-.044	-.076	.944

a. Dependent Variable: Basalarea

E. johnsonii/*E. subcrenulata* linear regression with altitude

Survival

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.168[a]	.028	-.069	.26117

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.020	1	.020	.292	.601[b]
	Residual	.682	10	.068		
	Total	.702	11			

a. Dependent Variable: Survival
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.695	.476		1.461	.175
	Altitude	.000	.001	-.168	-.540	.601

a. Dependent Variable: Survival

Height

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.180[a]	.032	-.065	2.56804

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.196	1	2.196	.333	.577[b]
	Residual	65.948	10	6.595		
	Total	68.144	11			

a. Dependent Variable: Height
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	23.958	4.676		5.123	.000
	Altitude	-.003	.006	-.180	-.577	.577

a. Dependent Variable: Height

Basal area

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.138[a]	.019	-.079	.20296

a. Predictors: (Constant), Altitude

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.008	1	.008	.193	.670[b]
	Residual	.412	10	.041		
	Total	.420	11			

a. Dependent Variable: Basalarea
b. Predictors: (Constant), Altitude

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.434	.370		1.173	.268
	Altitude	.000	.000	-.138	-.440	.670

a. Dependent Variable: Basalarea

Appendix 6.2 Comparison of basal area, height and survival by species.

Species - 1 *E. delegatensis*, 2 *E. coccifera*, 3 *E. subcrenulata*, 4 *E. johnstonii*, 5 *E. nitida*, 6 (*E. delegatensis var tasmaniensis*)

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	species	Statistic	df	Sig.	Statistic	df	Sig.
survival	1.00	.265	8	.104	.777	8	.016
	2.00	.276	8	.073	.909	8	.350
	3.00	.220	15	.049	.918	15	.182
	4.00	.197	19	.050	.810	19	.002
	5.00	.260	2	.			
	6.00	.268	11	.026	.829	11	.023
BA	1.00	.163	8	.200*	.970	8	.896
	2.00	.206	8	.200*	.927	8	.487
	3.00	.096	15	.200*	.972	15	.889
	4.00	.207	19	.032	.901	19	.050
	5.00	.260	2	.			
	6.00	.176	11	.200*	.911	11	.252
height	1.00	.183	8	.200*	.939	8	.599
	2.00	.193	8	.200*	.960	8	.813
	3.00	.133	15	.200*	.963	15	.740
	4.00	.123	19	.200*	.962	19	.603
	5.00	.260	2	.			
	6.00	.124	11	.200*	.976	11	.942
LNBA	1.00	.257	8	.129	.859	8	.118
	2.00	.215	8	.200*	.840	8	.075
	3.00	.114	15	.200*	.909	15	.133
	4.00	.139	19	.200*	.971	19	.788
	5.00	.260	2	.			
	6.00	.118	11	.200*	.963	11	.803
Asinsvl	1.00	.239	8	.200*	.805	8	.032
	2.00	.287	8	.052	.901	8	.297
	3.00	.225	15	.040	.858	15	.022
	4.00	.181	19	.102	.829	19	.003
	5.00	.260	2	.			
	6.00	.245	11	.065	.865	11	.067
LNheight	1.00	.180	8	.200*	.940	8	.614
	2.00	.170	8	.200*	.964	8	.850
	3.00	.116	15	.200*	.942	15	.408
	4.00	.176	19	.123	.864	19	.012
	5.00	.260	2	.			
	6.00	.141	11	.200*	.975	11	.934

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
survival	.989	5	99	.428
BA	4.656	5	57	.001
height	.607	5	57	.695
LNBA	1.176	5	57	.332
Asinsvl	3.731	5	99	.004
LNheight	.550	5	57	.738

LN basal area and height are normally distributed and also show equality of variances so t-tests assuming equal variances are appropriate:

For species 1 (*E. delegatensis*) and 6 (*E. delegatensis var tasmaniensis*)

Group Statistics

	species	N	Mean	Std. Deviation	Std. Error Mean
LNBA	6.00	11	-.91	.773	.233
	1.00	8	-.83	.542	.192
height	6.00	11	20.23	2.767	.834
	1.00	8	20.71	3.237	1.144

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
LNBA	Equal variances assumed	2.346	.144	-.238	17	.815	-.076	.319	-.750	.598
	Equal variances not assumed			-.252	16.995	.804	-.076	.302	-.713	.561
height	Equal variances assumed	.456	.509	-.347	17	.733	-.479	1.380	-3.390	2.432
	Equal variances not assumed			-.338	13.708	.740	-.479	1.416	-3.523	2.565

For species 2 (*E. coccifera*) and 5 (*E. nitida*)

Group Statistics

	species	N	Mean	Std. Deviation	Std. Error Mean
LNBA	5.00	2	-1.62	.281	.198
	2.00	8	-.95	.630	.223
height	5.00	2	19.88	1.025	.725
	2.00	8	21.87	3.006	1.063

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
LNBA	Equal variances assumed	.822	.391	-1.414	8	.195	-.668	.473	-1.758	.421
	Equal variances not assumed			-2.240	4.166	.086	-.668	.298	-1.484	.147
height	Equal variances assumed	1.167	.311	-.891	8	.399	-1.997	2.242	-7.166	3.172
	Equal variances not assumed			-1.552	5.975	.172	-1.997	1.287	-5.148	1.154

For species 3 (*E. subcrenulata*) and 4 (*E. johnstonii*).

Group Statistics

	species	N	Mean	Std. Deviation	Std. Error Mean
LNBA	4.00	19	-2.09	.751	.172
	3.00	15	-.88	.486	.125
height	4.00	19	21.12	4.465	1.024
	3.00	15	21.43	3.803	.982

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
LNBA	Equal variances assumed	2.241	.144	-5.393	32	.000	-1.208	.224	-1.664	-.752
	Equal variances not assumed			-5.668	30.961	.000	-1.208	.213	-1.642	-.773
height	Equal variances assumed	.183	.672	-.212	32	.834	-.306	1.447	-3.253	2.641
	Equal variances not assumed			-.216	31.779	.831	-.306	1.419	-3.197	2.585

Survival data were distributed in a way that differed from normal so non parametric Mann Whitney tests were used to determine if differences were significant.

For species 1 (*E. delegatensis*) and 6 (*E. delegatensis var tasmaniensis*)

Ranks

	species	N	Mean Rank	Sum of Ranks
survival	1.00	21	22.05	463.00
	6.00	24	23.83	572.00
	Total	45		

Test Statistics[a]

	survival
Mann-Whitney U	232.000
Wilcoxon W	463.000
Z	-.508
Asymp. Sig. (2-tailed)	.611

a. Grouping Variable: species

For species 2 (*E. coccifera*) and 5 (*E. nitida*)

Ranks

	species	N	Mean Rank	Sum of Ranks
survival	2.00	18	13.14	236.50
	5.00	6	10.58	63.50
	Total	24		

Test Statistics[a]

	survival
Mann-Whitney U	42.500
Wilcoxon W	63.500
Z	-.859
Asymp. Sig. (2-tailed)	.390
Exact Sig. [2*(1-tailed Sig.)]	.454[b]

a. Grouping Variable: species
b. Not corrected for ties.

For species 3 (*E. subcrenulata*) and 4 (*E. johnstonii*).

Ranks

	species	N	Mean Rank	Sum of Ranks
survival	3.00	15	27.70	415.50
	4.00	21	11.93	250.50
	Total	36		

Test Statistics[a]

	survival
Mann-Whitney U	19.500
Wilcoxon W	250.500
Z	-4.472
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: species
b. Not corrected for ties.

Appendix 6.3 Comparison of basal area, height and survival by selected origin.

E. delegatensis Groups: 1= origin 133, 2 = origin 131

Tests of Normality

	Group	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Survival	1.00	.385	3	.	.750	3	.000
	2.00	.295	3	.	.920	3	.452
Basalarea	1.00	.344	3	.	.841	3	.218
	2.00	.332	3	.	.864	3	.279
Height	1.00	.177	3	.	1.000	3	.967
	2.00	.316	3	.	.890	3	.355
LNbasalarea	1.00	.320	3	.	.883	3	.333
	2.00	.300	3	.	.913	3	.427
ARcsinsvvl	1.00	.385	3	.	.750	3	.000
	2.00	.295	3	.	.920	3	.452

a. Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Survival	5.203	1	4	.085
Basalarea	7.440	1	4	.053
Height	.021	1	4	.892
LNbasalarea	.001	1	4	.972
ARcsinsvvl	3.845	1	4	.121

Basal area and height are normally distributed and have equal variances so a t-test with equal variances is used to examine significance of differences:

Group Statistics

	Group	N	Mean	Std. Deviation	Std. Error Mean
Basalarea	1.00	3	.1900	.09797	.05657
	2.00	3	.7956	.41744	.24101
Height	1.00	3	23.3667	1.65025	.95277
	2.00	3	18.8167	1.35123	.78014

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Basalarea	Equal variances assumed	7.440	.053	-2.447	4	.071	-.60567	.24756	-1.29299	.08166
	Equal variances not assumed			-2.447	2.220	.122	-.60567	.24756	-1.57591	.36457
Height	Equal variances assumed	.021	.892	3.695	4	.021	4.55000	1.23142	1.13104	7.96896
	Equal variances not assumed			3.695	3.850	.022	4.55000	1.23142	1.07791	8.02209

Group 1 survival is significantly different from normal so a Mann Whitney test was used to determine if differences were significant, which they were not:

Ranks

	Group	N	Mean Rank	Sum of Ranks
Survival	1.00	3	2.17	6.50
	2.00	3	4.83	14.50
	Total	6		

Test Statistics[a]

	Survival
Mann-Whitney U	.500
Wilcoxon W	6.500
Z	-1.798
Asymp. Sig. (2-tailed)	.072
Exact Sig. [2*(1-tailed Sig.)]	.100[b]

a. Grouping Variable: Group
b. Not corrected for ties.

E. subcrenulata/ E. johnstonii: 1= origins 115-119, 2= origins 122-125, 3=origin 171

Tests of Normality

	Group	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Survival	1.00	.220	15	.049	.918	15	.182
	2.00	.253	12	.033	.772	12	.005
	3.00	.385	3	.	.750	3	.000
Basalarea	1.00	.096	15	.200*	.972	15	.889
	2.00	.220	12	.114	.934	12	.423
	3.00	.285	3	.	.932	3	.498
Height	1.00	.133	15	.200*	.963	15	.740
	2.00	.225	12	.095	.904	12	.179
	3.00	.314	3	.	.893	3	.365
LNbasalarea	1.00	.114	15	.200*	.909	15	.133
	2.00	.155	12	.200*	.930	12	.380
	3.00	.177	3	.	1.000	3	.974
ARcsinsvvl	1.00	.225	15	.040	.858	15	.022
	2.00	.241	12	.052	.794	12	.008
	3.00	.385	3	.	.750	3	.000

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Survival	.284	2	27	.755
Basalarea	2.541	2	27	.098
Height	.102	2	27	.904
LNbasalarea	1.103	2	27	.346
ARcsinsvvl	.172	2	27	.843

Basal area and height are normally distributed and exhibit equality of variances so an ANOVA is appropriate:

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Basalarea	Between Groups	.629	2	.314	13.196	.000
	Within Groups	.643	27	.024		
	Total	1.272	29			
Height	Between Groups	7.298	2	3.649	.192	.827
	Within Groups	513.879	27	19.033		
	Total	521.176	29			

There are significant differences in basal area so a Tukey's test is used to determine which groups of origins differ:

Multiple Comparisons

Dependent Variable: Basalarea
Tukey HSD

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
1.00	2.00	.29835*	.05977	.000	.1501	.4465
	3.00	.24678*	.09761	.045	.0048	.4888
2.00	1.00	-.29835*	.05977	.000	-.4465	-.1501
	3.00	-.05157	.09962	.863	-.2986	.1954
3.00	1.00	-.24678*	.09761	.045	-.4888	-.0048
	2.00	.05157	.09962	.863	-.1954	.2986

*. The mean difference is significant at the 0.05 level.

Basalarea

Tukey HSD[a,b]

Group	N	Subset for alpha = 0.05: 1	2
2.00	12	.1579	
3.00	3	.2094	
1.00	15		.4562
Sig.		.827	1.000

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 6.207.
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

For survival which is not normally distributed even after arcsine transformation, a Kruskal Wallis test was used to detect significant differences:

Ranks

	Group	N	Mean Rank
Survival	1.00	15	21.70
	2.00	12	8.83
	3.00	3	11.17
	Total	30	

Test Statistics[a,b]

	Survival
Chi-Square	15.507
df	2
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Group

As very highly significant differences exist Mann Whitney tests were used to determine differences between pairs:

1 vs 2

Ranks

	Group	N	Mean Rank	Sum of Ranks
Survival	1.00	15	18.90	283.50
	2.00	12	7.88	94.50
	Total	27		

Test Statistics[a]

	Survival
Mann-Whitney U	16.500
Wilcoxon W	94.500
Z	-3.632
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: Group
b. Not corrected for ties.

2 vs 3

Ranks

	Group	N	Mean Rank	Sum of Ranks
Survival	2.00	12	7.46	89.50
	3.00	3	10.17	30.50
	Total	15		

Test Statistics[a]

	Survival
Mann-Whitney U	11.500
Wilcoxon W	89.500
Z	-.980
Asymp. Sig. (2-tailed)	.327
Exact Sig. [2*(1-tailed Sig.)]	.365[b]

a. Grouping Variable: Group
b. Not corrected for ties.

1 vs 3

Ranks

	Group	N	Mean Rank	Sum of Ranks
Survival	1.00	15	10.80	162.00
	3.00	3	3.00	9.00
	Total	18		

Test Statistics[a]

	Survival
Mann-Whitney U	3.000
Wilcoxon W	9.000
Z	-2.384
Asymp. Sig. (2-tailed)	.017
Exact Sig. [2*(1-tailed Sig.)]	.017[b]

a. Grouping Variable: Group
b. Not corrected for ties.

Appendix 6.4 Comparison of basal area, height and survival of origins from the Hartz Mountains.

***E. johnstonii* – origins 121 to 125.**

Tests of Normality[b,c]

	Origin	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Basalarea	121.00	.260	2	.			
	122.00	.268	3	.	.951	3	.572
	123.00	.345	3	.	.838	3	.210
	124.00	.221	3	.	.986	3	.775
	125.00	.230	3	.	.981	3	.735
Height	121.00	.260	2	.			
	122.00	.297	3	.	.917	3	.441
	123.00	.296	3	.	.918	3	.447
	124.00	.301	3	.	.912	3	.425
	125.00	.303	3	.	.908	3	.412
LNBA	121.00	.260	2	.			
	122.00	.208	3	.	.992	3	.827
	123.00	.354	3	.	.822	3	.167
	124.00	.192	3	.	.997	3	.894
	125.00	.176	3	.	1.000	3	.982
Asinsvvl	122.00	.385	3	.	.750	3	.000
	123.00	.385	3	.	.750	3	.000
	124.00	.192	3	.	.997	3	.894
	125.00	.320	3	.	.884	3	.335
Survival	122.00	.385	3	.	.750	3	.000
	123.00	.385	3	.	.750	3	.000
	124.00	.175	3	.	1.000	3	1.000
	125.00	.315	3	.	.891	3	.356

a. Lilliefors Significance Correction
b. Asinsvvl is constant when Origin = 121.00. It has been omitted.
c. Survival is constant when Origin = 121.00. It has been omitted.

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Basalarea	1.356	4	9	.322
Height	2.175	4	9	.153
LNBA	1.557	4	9	.266

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Basalarea	Between Groups	.034	4	.008	1.093	.416
	Within Groups	.070	9	.008		
	Total	.104	13			
Height	Between Groups	121.455	4	30.364	1.822	.209
	Within Groups	150.017	9	16.669		
	Total	271.472	13			
LNBA	Between Groups	1.868	4	.467	.990	.461
	Within Groups	4.247	9	.472		
	Total	6.114	13			

KW test for survival as the data were not normally distributed:

Ranks

	Origin	N	Mean Rank
Survival	121.00	3	7.33
	122.00	3	8.50
	123.00	3	4.83
	124.00	3	6.33
	125.00	3	13.00
	Total	15	

Test Statistics[a,b]

	Survival
Chi-Square	6.125
df	4
Asymp. Sig.	.190

a. Kruskal Wallis Test
b. Grouping Variable: Origin

Appendix 7 Statistical supporting data for Newton Rigg Trial.

Appendix 7.1: Normality of RHG by species/ Mean planting height, percentage height growth and percentage survival by quartile.

(a) Normality of RHG by species

1=ash, 2=alder, 3=sycamore, 4=*E. gunnii*, 5=*E. nitens*

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Species	Statistic	df	Sig.	Statistic	df	Sig.
RHG	1.00	.080	275	.000	.940	275	.000
	2.00	.060	278	.016	.981	278	.001
	3.00	.179	244	.000	.765	244	.000
	4.00	.255	251	.000	.341	251	.000
	5.00	.046	271	.200*	.983	271	.002

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Only RHG for *E. nitens* is normally distributed (Kolmogorov-Smirnove test).

(b) Mean planting height, percentage height growth and percentage survival by quartile.

(1) <u>Planting height</u>

***E. gunnii* planting height by quartile**

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Quartile	Statistic	df	Sig.	Statistic	df	Sig.
LNpht	1.00	.167	63	.000	.876	63	.000
	2.00	.230	63	.000	.860	63	.000
	3.00	.190	62	.000	.884	62	.000
	4.00	.122	62	.022	.927	62	.001
Pht	1.00	.155	63	.001	.899	63	.000
	2.00	.225	63	.000	.861	63	.000
	3.00	.194	62	.000	.884	62	.000
	4.00	.138	62	.005	.911	62	.000

a. Lilliefors Significance Correction

Both planting height and LN planting height significantly different from normal distribution so non parametric tests (Kruskal Wallis and Mann Whitney tests) applied.

Kruskall Wallis

Ranks

	Quartile	N	Mean Rank
Pht	1.00	63	32.06
	2.00	63	94.94
	3.00	62	157.56
	4.00	62	219.44
	Total	250	

Test Statistics[a,b]

	Pht
Chi-Square	233.843
df	3
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Quartile

Mann Whitney tests:

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	1.00	63	32.06	2020.00
	2.00	63	94.94	5981.00
	Total	126		

Test Statistics[a]

	Pht
Mann-Whitney U	4.000
Wilcoxon W	2020.000
Z	-9.716
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	1.00	63	32.00	2016.00
	3.00	62	94.50	5859.00
	Total	125		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2016.000
Z	-9.691
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	1.00	63	32.00	2016.00
	4.00	62	94.50	5859.00
	Total	125		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2016.000
Z	-9.662
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	2.00	63	32.00	2016.00
	3.00	62	94.50	5859.00
	Total	125		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2016.000
Z	-9.724
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	2.00	63	32.00	2016.00
	4.00	62	94.50	5859.00
	Total	125		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2016.000
Z	-9.694
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	3.00	62	31.56	1957.00
	4.00	62	93.44	5793.00
	Total	124		

Test Statistics[a]

	Pht
Mann-Whitney U	4.000
Wilcoxon W	1957.000
Z	-9.631
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

E. nitens planting height by quartile

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Quartile	Statistic	df	Sig.	Statistic	df	Sig.
Pht	1.00	.196	69	.000	.882	69	.000

	2.00	.154	69	.000	.929	69	.001
	3.00	.190	69	.000	.874	69	.000
	4.00	.133	69	.004	.860	69	.000

a. Lilliefors Significance Correction

Planting height not normally distributed so non parametric tests (Kruskal Wallis and Mann Whitney tests) used to detect differences between quartiles.

Kruskal Wallis

Ranks

	Quartile	N	Mean Rank
Pht	1.00	69	35.52
	2.00	69	103.91
	3.00	69	172.66
	4.00	69	241.91
	Total	276	

Test Statistics[a,b]

	Pht
Chi-Square	256.926
df	3
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Quartile

Mann Whitney

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	1.00	69	35.52	2451.00
	2.00	69	103.48	7140.00
	Total	138		

Test Statistics[a]

	Pht
Mann-Whitney U	36.000
Wilcoxon W	2451.000
Z	-10.026
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	1.00	69	35.00	2415.00
	3.00	69	104.00	7176.00
	Total	138		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2415.000
Z	-10.192
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	1.00	69	35.00	2415.00
	4.00	69	104.00	7176.00
	Total	138		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2415.000
Z	-10.160
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	2.00	69	35.43	2445.00
	3.00	69	103.57	7146.00
	Total	138		

Test Statistics[a]

	Pht
Mann-Whitney U	30.000
Wilcoxon W	2445.000
Z	-10.085
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	2.00	63	32.00	2016.00
	4.00	62	94.50	5859.00
	Total	125		

Test Statistics[a]

	Pht
Mann-Whitney U	.000
Wilcoxon W	2016.000
Z	-9.694
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
Pht	3.00	69	35.09	2421.50
	4.00	69	103.91	7169.50
	Total	138		

Test Statistics[a]

	Pht
Mann-Whitney U	6.500
Wilcoxon W	2421.500
Z	-10.167
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Quartile

2) Percentage height growth

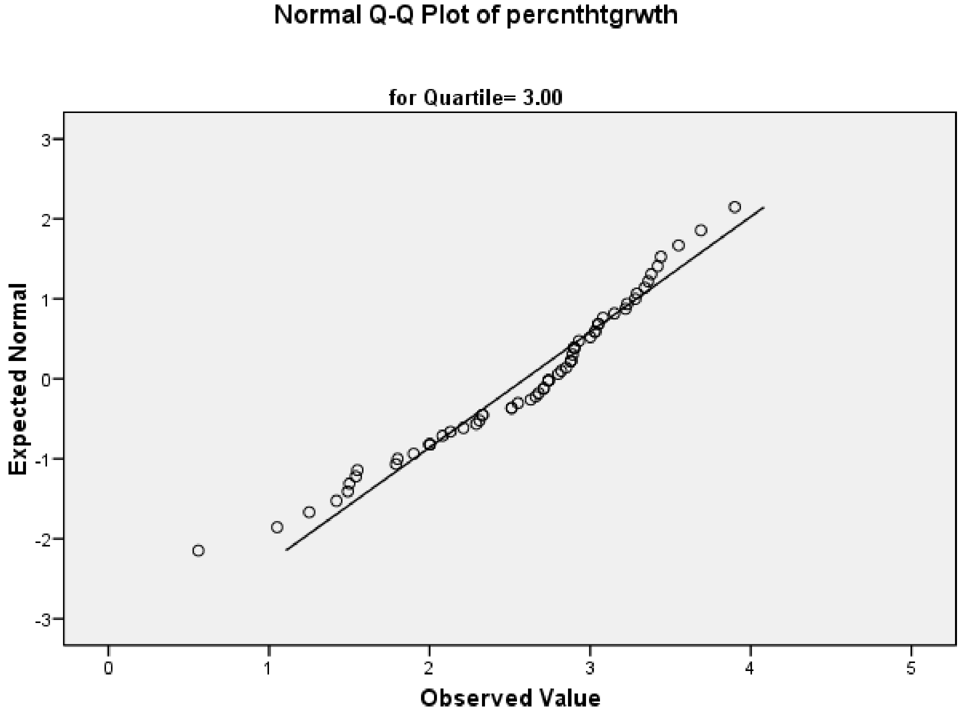
E. gunnii percentage height growth by quartile

All but 3rd quartile data was normal – plotting data third quartile looked normal...

Tests of Normality

	Quartile	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
percnthtgrwth	1.00	.100	63	.186	.974	63	.193
	2.00	.103	63	.097	.972	63	.166
	3.00	.135	62	.007	.956	62	**.026**
	4.00	.085	62	.200(*)	.984	62	.571

* This is a lower bound of the true significance.
a Lilliefors Significance Correction



Variances not significantly different for percent height growth:

Test of Homogeneity of Variances

percnthtgrwth

Levene Statistic	df1	df2	Sig.
2.499	3	246	.060

As such an ANOVA was used to determine if differences in percentage height growth by quartile were significantly different:

ANOVA

percnthtgrwth

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	41.227	3	13.742	19.710	.000
Within Groups	171.519	246	.697		
Total	212.746	249			

Differences were very highly significant so a Tukey post hoc test was performed:

Multiple Comparisons

Dependent Variable: percnthtgrwth
Tukey HSD

(I) Quartile	(J) Quartile	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Upper Bound	Lower Bound
1.00	2.00	.72556(*)	.14878	.000	.3407	1.1104
	3.00	.88152(*)	.14938	.000	.4951	1.2679
	4.00	1.07120(*)	.14938	.000	.6848	1.4576
2.00	1.00	-.72556(*)	.14878	.000	-1.1104	-.3407
	3.00	.15597	.14938	.724	-.2304	.5424
	4.00	.34565	.14938	.098	-.0407	.7320
3.00	1.00	-.88152(*)	.14938	.000	-1.2679	-.4951
	2.00	-.15597	.14938	.724	-.5424	.2304
	4.00	.18968	.14997	.586	-.1983	.5776
4.00	1.00	-1.07120(*)	.14938	.000	-1.4576	-.6848
	2.00	-.34565	.14938	.098	-.7320	.0407
	3.00	-.18968	.14997	.586	-.5776	.1983

* The mean difference is significant at the .05 level.

E. nitens **percentage height growth by quartile**

Two quartiles percent growth data not normal

Tests of Normality

	Quartile	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
percnthtgrwth	1.00	.089	69	.200(*)	.971	69	.109
	2.00	.112	68	.033	.951	68	.010
	3.00	.055	69	.200(*)	.990	69	.858
	4.00	.103	69	.069	.950	69	.008

* This is a lower bound of the true significance.
a Lilliefors Significance Correction

So a KW test used to detect differences:

Ranks

	Quartile	N	Mean Rank
percnthtgrwth	1.00	69	184.67
	2.00	68	131.65
	3.00	69	119.22
	4.00	69	116.37
	Total	275	

Test Statistics(a,b)

	percnthtgrwth
Chi-Square	33.145
df	3
Asymp. Sig.	.000

a Kruskal Wallis Test
b Grouping Variable: Quartile

Highly significant
Mann Whitney tests to test differences
1 vs 2

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
percnthtgrwth	1.00	69	82.09	5664.50
	2.00	68	55.71	3788.50
	Total	137		

Test Statistics(a)

	percnthtgrwth
Mann-Whitney U	1442.500
Wilcoxon W	3788.500
Z	-3.890
Asymp. Sig. (2-tailed)	.000

a Grouping Variable: Quartile

1 vs 3 **Ranks**

	Quartile	N	Mean Rank	Sum of Ranks
percnthtgrwth	1.00	69	85.54	5902.50
	3.00	69	53.46	3688.50
	Total	138		

Test Statistics(a)

	percnthtgrwth
Mann-Whitney U	1273.500
Wilcoxon W	3688.500
Z	-4.714
Asymp. Sig. (2-tailed)	.000

a Grouping Variable: Quartile

1 vs 4

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
percnthtgrwth	1.00	69	87.03	6005.00
	4.00	69	51.97	3586.00
	Total	138		

Test Statistics(a)

	percnthtgrwth
Mann-Whitney U	1171.000
Wilcoxon W	3586.000
Z	-5.151
Asymp. Sig. (2-tailed)	.000

a Grouping Variable: Quartile

2 vs 3

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
percnthtgrwth	2.00	68	71.92	4890.50
	3.00	69	66.12	4562.50
	Total	137		

Test Statistics(a)

	percnthtgrwth
Mann-Whitney U	2147.500
Wilcoxon W	4562.500
Z	-.855
Asymp. Sig. (2-tailed)	.393

a Grouping Variable: Quartile

2 vs 4

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
percnthtgrwth	2.00	68	73.02	4965.50
	4.00	69	65.04	4487.50
	Total	137		

Test Statistics(a)

	percnthtgrwth
Mann-Whitney U	2072.500
Wilcoxon W	4487.500
Z	-1.177
Asymp. Sig. (2-tailed)	.239

a Grouping Variable: Quartile

2 vs 3

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
percnthtgrwth	3.00	69	69.64	4805.00
	4.00	69	69.36	4786.00
	Total	138		

Test Statistics(a)

	percnthtgrwth
Mann-Whitney U	2371.000
Wilcoxon W	4786.000
Z	-.040
Asymp. Sig. (2-tailed)	.968

a Grouping Variable: Quartile

<u>2) Survival</u>

***E. gunnii* survival by quartile**

Quartile 2 survival vs 76.4% survival (quartile 1) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	64	.889	.764	.006(a)
	Group 2	.00	8	.111		
	Total		72	1.000		

a Based on Z Approximation.

Quartile 3 survival vs 76.4% survival (quartile 1) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	68	.944	.764	.000(a)
	Group 2	.00	4	.056		
	Total		72	1.000		

a Based on Z Approximation.

Quartile 4 survival vs 76.4% survival (quartile 1) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	63	.875	.764	.014(a)
	Group 2	.00	9	.125		
	Total		72	1.000		

a Based on Z Approximation.

Quartile 3 vs 88.9% (Quartile 2) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	68	.944	.889	.087(a)
	Group 2	.00	4	.056		
	Total		72	1.000		

a Based on Z Approximation.

Quartile 3 vs 87.5% (Quartile 4) **Binomial Test**

	Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)

Survl	Group 1	1.00	68	.944	.875	.044(a)
	Group 2	.00	4	.056		
	Total		72	1.000		

a Based on Z Approximation.

Quartile 2 vs 87.5 % (quartile 4) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	64	.889	.875	.447(a)
	Group 2	.00	8	.111		
	Total		72	1.000		

a Based on Z Approximation.

E. nitens survival by quartile

Quartile 2 survival vs 90.3% survival (quartile 1) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	70	.972222	.903000	.025(a)
	Group 2	.00	2	.027778		
	Total		72	1.000000		

a Based on Z Approximation.

Quartile 3 survival vs 90.3% survival (quartile 1) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	69	.958333	.903000	.072(a)
	Group 2	.00	3	.041667		
	Total		72	1.000000		

a Based on Z Approximation.

Quartile 4 survival vs 90.3% survival (quartile 1) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	71	.986111	.903000	.006(a)
	Group 2	.00	1	.013889		
	Total		72	1.000000		

a Based on Z Approximation.

Quartile 3 vs 97.2% (Quartile 2) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	69	.958333	.972000	.328(a,b)
	Group 2	.00	3	.041667		
	Total		72	1.000000		

a Alternative hypothesis states that the proportion of cases in the first group < .972000.
b Based on Z Approximation.

Quartile 3 vs 98.6% (Quartile 4) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	69	.958	.986	.080(a,b)
	Group 2	.00	3	.042		
	Total		72	1.000		

a Alternative hypothesis states that the proportion of cases in the first group < .986.
b Based on Z Approximation.

Quartile 4 vs 97.2 % (quartile 2) **Binomial Test**

		Category	N	Observed Prop.	Test Prop.	Asymp. Sig. (1-tailed)
Survl	Group 1	1.00	71	.986111	.972000	.398(a)
	Group 2	.00	1	.013889		
	Total		72	1.000000		

a Based on Z Approximation.

Appendix 7.2: One year results of *E. nitens* and E. gunnii, 2010 planting

Analysis by species: 1=*E. gunnii, E. nitens* = 2

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Plantht	1.00	.116	57	.054	.966	57	.113
	2.00	.103	103	.010	.985	103	.289
Yr1ht	1.00	.072	57	.200*	.987	57	.792
	2.00	.059	103	.200*	.991	103	.708
htgrow	1.00	.051	57	.200*	.992	57	.975
	2.00	.059	103	.200*	.987	103	.417
RHG	1.00	.099	57	.200*	.942	57	.008
	2.00	.086	103	.059	.963	103	.006
LNRHG	1.00	.122	57	.034	.899	57	.000
	2.00	.091	103	.037	.947	103	.000

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Planting height, year 1 height, height growth are all normally distributed so test for equality of variances:

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Plantht	2.585	1	158	.110
Yr1ht	1.461	1	158	.229
htgrow	1.362	1	158	.245

They are not significantly different so conduct an ANOVA:

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Plantht	Between Groups	2723.273	1	2723.273	141.283	.000
	Within Groups	3045.502	158	19.275		
	Total	5768.775	159			
Yr1ht	Between Groups	1801.058	1	1801.058	4.018	.047
	Within Groups	70826.842	158	448.271		
	Total	72627.900	159			
htgrow	Between Groups	94.987	1	94.987	.212	.646
	Within Groups	70759.988	158	447.848		
	Total	70854.975	159			

RHG (even when LN transformed) different from normal so non parametric Mann Whitney test applied:

Ranks

	Species	N	Mean Rank	Sum of Ranks
RHG	1.00	57	106.34	6061.50
	2.00	103	66.20	6818.50
	Total	160		

Test Statistics[a]

	RHG
Mann-Whitney U	1462.500
Wilcoxon W	6818.500
Z	-5.248
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: Species

Analysis by blocks

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Block	Statistic	df	Sig.	Statistic	df	Sig.
Yr1ht	1.00	.120	26	.200*	.956	26	.313
	2.00	.129	23	.200*	.982	23	.941
	3.00	.127	25	.200*	.968	25	.589
	4.00	.091	32	.200*	.968	32	.447
	5.00	.080	28	.200*	.989	28	.987
	6.00	.130	26	.200*	.932	26	.085
htgrow	1.00	.104	26	.200*	.957	26	.341
	2.00	.135	23	.200*	.929	23	.104
	3.00	.108	25	.200*	.955	25	.317
	4.00	.076	32	.200*	.986	32	.945
	5.00	.094	28	.200*	.989	28	.990
	6.00	.134	26	.200*	.961	26	.411
RHG	1.00	.133	26	.200*	.943	26	.161
	2.00	.240	23	.001	.865	23	.005
	3.00	.174	25	.049	.828	25	.001
	4.00	.165	32	.027	.817	32	.000
	5.00	.107	28	.200*	.978	28	.794
	6.00	.077	26	.200*	.989	26	.989
LNPlantht	1.00	.126	26	.200*	.942	26	.153
	2.00	.200	23	.017	.918	23	.061
	3.00	.114	25	.200*	.965	25	.519
	4.00	.206	32	.001	.910	32	.011
	5.00	.147	28	.127	.950	28	.195
	6.00	.128	26	.200*	.918	26	.041
LNYr1ht	1.00	.154	26	.112	.945	26	.181
	2.00	.118	23	.200*	.975	23	.810
	3.00	.096	25	.200*	.972	25	.707
	4.00	.139	32	.117	.933	32	.048
	5.00	.136	28	.198	.960	28	.349
	6.00	.207	26	.006	.828	26	.001
LNhtgrow	1.00	.179	26	.032	.899	26	.015
	2.00	.160	23	.129	.931	23	.115
	3.00	.161	25	.093	.940	25	.148
	4.00	.169	32	.020	.843	32	.000
	5.00	.122	28	.200*	.920	28	.034
	6.00	.245	26	.000	.745	26	.000
LNRHG	1.00	.162	26	.076	.912	26	.029
	2.00	.163	23	.117	.931	23	.114
	3.00	.129	25	.200*	.974	25	.756
	4.00	.125	32	.200*	.941	32	.082
	5.00	.102	28	.200*	.964	28	.441
	6.00	.139	26	.200*	.860	26	.002
Plantht	1.00	.103	26	.200*	.974	26	.724
	2.00	.185	23	.041	.930	23	.110
	3.00	.143	25	.200*	.964	25	.493

4.00	.161	32	.035	.940	32	.074
5.00	.112	28	.200*	.973	28	.666
6.00	.082	26	.200*	.977	26	.815

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Yr1 height, Planting height and height growth were normally distributed so test for equality of variances:

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Yr1ht	2.003	5	154	.081
Plantht	4.528	5	154	.001
htgrow	1.810	5	154	.114

Yr1 height and height growth have equality of variances so conduct an ANOVA to test for significant differences between blocks:

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Yr1ht	Between Groups	4381.111	5	876.222	1.977	.085
	Within Groups	68246.789	154	443.161		
	Total	72627.900	159			
htgrow	Between Groups	3496.652	5	699.330	1.599	.164
	Within Groups	67358.323	154	437.392		
	Total	70854.975	159			

For Planting height (as variances not equal) and for RHG (as not normal) a Kruskal Wallis test was used to test for significant differences between blocks:

Ranks

	Block	N	Mean Rank
Plantht	1.00	26	82.44
	2.00	23	80.39
	3.00	25	73.72
	4.00	32	88.80
	5.00	28	87.70
	6.00	26	67.21
	Total	160	
RHG	1.00	26	76.40
	2.00	23	84.76
	3.00	25	71.44
	4.00	32	74.39
	5.00	28	89.82
	6.00	26	87.02
	Total	160	

Test Statistics[a,b]

	Plantht	RHG
Chi-Square	4.437	3.558
df	5	5
Asymp. Sig.	.488	.615

a. Kruskal Wallis Test
b. Grouping Variable: Block

Appendix 7.3: Survival of *E. nitens* and *E. gunnii* after one growing season

By species 1=*E. gunnii*, 2 = *E.nitens*

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Prcntsurvival	1.00	.296	6	.110	.887	6	.301
	2.00	.126	6	.200*	.984	6	.971
Arcsinpercentsvl	1.00	.310	6	.073	.845	6	.144
	2.00	.142	6	.200*	.972	6	.904

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Levene's test and T-test

Group Statistics

	Species	N	Mean	Std. Deviation	Std. Error Mean
Prcntsurvival	1.00	6	.6027	.19403	.07921
	2.00	6	.7071	.13400	.05470

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upp
Prcntsurvival	Equal variances assumed	.688	.426	-1.084	10	.304	-.10431	.09627	-.31880	
	Equal variances not assumed			-1.084	8.886	.307	-.10431	.09627	-.32251	

Variances equal and differences not significant

Appendix 7.4: One year growth of birch and E. gunnii, 2011 planting

Analysis by species 1=birch, 2=*E. gunnii*

Tests of Normality

	Species	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Plantht	1.00	.080	280	.000	.963	280	.000
	2.00	.075	238	.003	.988	238	.040
Yr1ht	1.00	.048	280	.200(*)	.987	280	.014
	2.00	.049	238	.200(*)	.988	238	.052
Yr1grwth	1.00	.049	280	.100	.986	280	.007
	2.00	.055	238	.080	.988	238	.041
Percntgrwth	1.00	.145	280	.000	.711	280	.000
	2.00	.093	238	.000	.916	238	.000

* This is a lower bound of the true significance.
a Lilliefors Significance Correction

Tests of Normality

	Species	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
LNPlantHt	1.00	.140	279	.000	.788	279	.000
	2.00	.144	238	.000	.862	238	.000
LNYr1ht	1.00	.095	279	.000	.916	279	.000
	2.00	.117	238	.000	.924	238	.000
LNprcgwth	1.00	.129	279	.000	.784	279	.000
	2.00	.150	238	.000	.848	238	.000

a Lilliefors Significance Correction

The variables were not normally distributed so Kruskal Wallis tests were used to detect significant differences by species:

Ranks

	Species	N	Mean Rank
Plantht	1.00	287	381.39
	2.00	283	188.25
	Total	570	
Yr1ht	1.00	284	343.81
	2.00	249	179.40
	Total	533	
Yr1grwth	1.00	280	325.81
	2.00	247	193.93
	Total	527	
Percntgrwth	1.00	283	262.99
	2.00	238	258.63
	Total	521	

Test Statistics(a,b)

	Plantht	Yr1ht	Yr1grwth	Percntgrwth
Chi-Square	196.501	151.239	98.463	.108
df	1	1	1	1
Asymp. Sig.	.000	.000	.000	.742

a Kruskal Wallis Test
b Grouping Variable: Species

Analysis by blocks

Tests of Normality

		Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Block	Statistic	df	Sig.	Statistic	df	Sig.
LNPlantHt	1.00	.106	92	.012	.975	92	.077
	2.00	.155	92	.000	.889	92	.000
	3.00	.135	88	.000	.848	88	.000
	4.00	.156	75	.000	.873	75	.000
	5.00	.083	92	.132	.972	92	.042
	6.00	.201	78	.000	.739	78	.000
LNYr1ht	1.00	.119	92	.003	.880	92	.000
	2.00	.128	92	.001	.858	92	.000
	3.00	.075	88	.200(*)	.965	88	.018
	4.00	.158	75	.000	.870	75	.000
	5.00	.196	92	.000	.844	92	.000
	6.00	.158	78	.000	.920	78	.000
LNprcgwth	1.00	.144	92	.000	.810	92	.000
	2.00	.156	92	.000	.688	92	.000
	3.00	.104	88	.021	.915	88	.000
	4.00	.160	75	.000	.824	75	.000
	5.00	.219	92	.000	.737	92	.000
	6.00	.173	78	.000	.855	78	.000
Plantht	1.00	.080	92	.189	.979	92	.154
	2.00	.104	92	.015	.975	92	.071
	3.00	.073	88	.200(*)	.974	88	.073
	4.00	.104	75	.043	.966	75	.043
	5.00	.079	92	.200(*)	.984	92	.308
	6.00	.121	78	.007	.945	78	.002
Yr1ht	1.00	.065	92	.200(*)	.984	92	.339
	2.00	.090	92	.062	.982	92	.238
	3.00	.076	88	.200(*)	.986	88	.460
	4.00	.097	75	.078	.965	75	.037
	5.00	.131	92	.001	.967	92	.021
	6.00	.120	78	.007	.953	78	.006
Yr1grwth	1.00	.068	92	.200(*)	.985	92	.377
	2.00	.071	92	.200(*)	.982	92	.218
	3.00	.058	88	.200(*)	.992	88	.900
	4.00	.076	75	.200(*)	.969	75	.061
	5.00	.091	92	.059	.979	92	.153
	6.00	.115	78	.013	.951	78	.005

The data was not normally distributed so a Kruskal Wallis test was used:

Ranks

	Block	N	Mean Rank
Plantht	1.00	96	317.31
	2.00	96	268.36
	3.00	96	292.69
	4.00	93	296.03
	5.00	96	261.66
	6.00	93	277.02
	Total	570	
Yr1ht	1.00	93	297.03
	2.00	93	311.45
	3.00	91	275.93
	4.00	79	210.46
	5.00	94	269.20
	6.00	83	225.08
	Total	533	
Yr1grwth	1.00	93	287.61
	2.00	93	317.66
	3.00	88	267.71
	4.00	79	196.68
	5.00	94	273.62
	6.00	80	225.28
	Total	527	
Percntgrwth	1.00	92	264.11
	2.00	92	330.39
	3.00	91	251.45
	4.00	76	189.64
	5.00	93	286.46
	6.00	77	225.34
	Total	521	

Test Statistics(a,b)

	Plantht	Yr1ht	Yr1grwth	Percntgrwth
Chi-Square	7.463	28.410	34.832	44.005
df	5	5	5	5
Asymp. Sig.	.188	.000	.000	.000

a Kruskal Wallis Test
b Grouping Variable: Block

SURVIVAL

Tests of Normality(b,c)

	Block	Kolmogorov-Smirnov(a) Statistic	df	Sig.
Survival	1.00	.260	2	.
	2.00	.260	2	.
	4.00	.260	2	.
	5.00	.260	2	.
	6.00	.260	2	.
ASinSvl	1.00	.260	2	.
	2.00	.260	2	.
	4.00	.260	2	.
	5.00	.260	2	.
	6.00	.260	2	.

a Lilliefors Significance Correction
b Survival is constant when Block = 3.00. It has been omitted.
c ASinSvl is constant when Block = 3.00. It has been omitted.

Tests of Normality

		Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Species	Statistic	df	Sig.	Statistic	df	Sig.
Survival	1.00	.277	6	.168	.800	6	.059
	2.00	.347	6	.023	.774	6	.034
ASinSvl	1.00	.303	6	.090	.812	6	.075
	2.00	.319	6	.056	.806	6	.067

a Lilliefors Significance Correction

KW survival by blocks

Ranks

	Block	N	Mean Rank
Survival	1.00	2	8.50
	2.00	2	8.50
	3.00	2	3.50
	4.00	2	5.00
	5.00	2	9.50
	6.00	2	4.00
	Total	12	

Test Statistics(a,b)

	Survival
Chi-Square	5.480
df	5
Asymp. Sig.	.360

a Kruskal Wallis Test
b Grouping Variable: Block

T test for ASin survival by species

Group Statistics

	Species	N	Mean	Std. Deviation	Std. Error Mean
ASinSvl	1.00	6	1.4557	.13502	.05512
	2.00	6	1.2097	.17421	.07112

Independent Samples t Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
		Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
ASinSvl	Equal variances assumed	.892	.367	2.734	10	.021	.24604	.08998	.04555	.44653
	Equal variances not assumed			2.734	9.414	.022	.24604	.08998	.04384	.44823

Variances equal and differences are significant

Appendix 7.5: Survival of *Birch* and *E. gunnii* after one growing season

1=birch, 2=*E. gunnii*,

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Survival	1.00	.277	6	.168	.800	6	.059
	2.00	.298	6	.104	.807	6	.068

a. Lilliefors Significance Correction

Not different from normal so use a t-test

T-test

Group Statistics

	Species	N	Mean	Std. Deviation	Std. Error Mean
Survival	1.00	6	.9722	.03648	.01489
	2.00	6	.8542	.12430	.05075

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Survival	Equal variances assumed	12.308	.006	2.232	10	.050	.11806	.05289	.00022	.23590
	Equal variances not assumed			2.232	5.855	.068	.11806	.05289	-.01214	.24825

Variances not equal and so differences not significant.

Appendix 7.6 3 year height, height growth, relative height growth and survival by species.

1=ash, 2=alder, 3=sycamore

Height, height growth, relative height growth

Tests of Normality

	Species	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Pheight	1.00	.080	139	.031	.983	139	.083
	2.00	.091	149	.004	.976	149	.010
	3.00	.056	220	.091	.993	220	.380
LNPheight	1.00	.084	139	.017	.978	139	.025
	2.00	.094	149	.003	.987	149	.169
	3.00	.105	220	.000	.962	220	.000
Yr3height	1.00	.054	139	.200*	.979	139	.031
	2.00	.075	149	.037	.972	149	.004
	3.00	.080	220	.002	.956	220	.000
Htgrow	1.00	.055	139	.200*	.971	139	.005
	2.00	.076	149	.037	.972	149	.004
	3.00	.075	220	.004	.957	220	.000
RGR	1.00	.081	139	.027	.951	139	.000
	2.00	.066	149	.200*	.982	149	.047
	3.00	.079	220	.002	.917	220	.000

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.

Tests of Normality

	Species	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
LNPheight	1.00	.084	139	.017	.978	139	.025
	2.00	.094	149	.003	.987	149	.169
	3.00	.105	220	.000	.962	220	.000
LNYr3height	1.00	.104	139	.001	.730	139	.000
	2.00	.094	149	.003	.957	149	.000
	3.00	.055	220	.200*	.986	220	.024
LNHtGrow	1.00	.108	139	.000	.958	139	.000
	2.00	.093	149	.003	.951	149	.000
	3.00	.095	220	.000	.939	220	.000
LNRGR	1.00	.083	139	.020	.969	139	.003
	2.00	.080	149	.021	.964	149	.001
	3.00	.087	220	.000	.955	220	.000

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.

None of the variables had the data for all species normally distributed so a Kruskal Wallis test was applied to planting height, year 3 height, height growth and relative growth rate.

Kruskal Wallis

Ranks

	Species	N	Mean Rank
Pheight	1.00	288	409.83
	2.00	288	205.15
	3.00	288	682.52
	Total	864	
Yr3height	1.00	141	197.73
	2.00	151	379.23
	3.00	222	212.66
	Total	514	
Htgrow	1.00	139	210.18
	2.00	149	390.80
	3.00	220	190.19
	Total	508	
RGR	1.00	139	240.85
	2.00	149	420.61
	3.00	220	150.62
	Total	508	

Test Statistics[a,b]

	Pheight	Yr3height	Htgrow	RGR
Chi-Square	531.164	144.510	183.374	302.181
df	2	2	2	2
Asymp. Sig.	.000	.000	.000	.000

a. Kruskal Wallis Test
b. Grouping Variable: Species

To examine where the sources of these significant differences MannWhitney test were sued to compare pairs of species:

1 vs 2

Test Statistics[a]

	Pheight	Yr3height	Htgrow	RGR
Mann-Whitney U	15551.500	3132.000	2586.500	1352.500
Wilcoxon W	57167.500	13143.000	12316.500	11082.500
Z	-13.002	-10.421	-11.001	-12.748
Asymp. Sig. (2-tailed)	.000	.000	.000	.000

a. Grouping Variable: Species

1 vs 3

Test Statistics[a]

	Pheight	Yr3height	Htgrow	RGR
Mann-Whitney U	9023.500	14736.500	13681.000	8184.000
Wilcoxon W	50639.500	24747.500	37991.000	32494.000
Z	-16.256	-.939	-1.680	-7.419
Asymp. Sig. (2-tailed)	.000	.348	.093	.000

a. Grouping Variable: Species

2 vs 3

Test Statistics[a]

	Pheight	Yr3height	Htgrow	RGR
Mann-Whitney U	1915.500	5893.000	3850.000	642.500
Wilcoxon W	43531.500	30646.000	28160.000	24952.500
Z	-19.822	-10.633	-12.474	-15.664
Asymp. Sig. (2-tailed)	.000	.000	.000	.000

a. Grouping Variable: Species

Survival

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
percsrv	1.00	.239	6	.200*	.917	6	.484
	2.00	.281	6	.150	.839	6	.127
	3.00	.255	6	.200*	.875	6	.247
n	1.00	.239	6	.200*	.917	6	.484
	2.00	.281	6	.150	.839	6	.127
	3.00	.255	6	.200*	.875	6	.247
arcsinsvl	1.00	.244	6	.200*	.915	6	.467
	2.00	.268	6	.200*	.833	6	.113
	3.00	.234	6	.200*	.886	6	.298

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
arcsinsvl	.443	2	15	.650
percsrv	.915	2	15	.422
n	.915	2	15	.422

All variables meet the requirements of an ANOVA as the data were normal and exhibited equality of variances:

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
arcsinsvl	Between Groups	.565	2	.282	1.915	.182
	Within Groups	2.212	15	.147		
	Total	2.777	17			
percsrv	Between Groups	.293	2	.146	2.008	.169
	Within Groups	1.093	15	.073		
	Total	1.386	17			
n	Between Groups	674.111	2	337.056	2.008	.169
	Within Groups	2518.167	15	167.878		
	Total	3192.278	17			

Appendix 7.7 Comparison of diameter and height by species after two growing seasons.

Species: 1 = Alder, 2 = Ash, 3= *E. gunnii*, 4= sycamore

Tests of Normality

	Species	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
diam2010	1.00	.186	12	.200*	.942	12	.523
	2.00	.167	11	.200*	.915	11	.278
	3.00	.262	12	.022	.818	12	.015
	4.00	.169	12	.200*	.889	12	.116
height2010	1.00	.141	12	.200*	.962	12	.810
	2.00	.254	11	.045	.906	11	.217
	3.00	.149	12	.200*	.935	12	.440
	4.00	.153	12	.200*	.935	12	.434
LNdiam2010	1.00	.213	12	.140	.936	12	.445
	2.00	.213	11	.176	.885	11	.119
	3.00	.244	12	.047	.844	12	.031
	4.00	.173	12	.200*	.901	12	.165

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
diam2010	3.839	3	43	.016
height2010	.288	3	44	.834

Height variances not significantly different and normally distributed so use an ANOVA and a post hoc test.

ANOVA

height2010

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	56407.896	3	18802.632	19.682	.000
Within Groups	42034.083	44	955.320		
Total	98441.979	47			

Post Hoc Test

Multiple Comparisons

Dependent Variable: height2010
Tukey HSD

(I) Species	(J) Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
1.00	2.00	49.91667*	12.61824	.002	16.2259	83.6074
	3.00	-42.50000*	12.61824	.008	-76.1908	-8.8092
	4.00	26.16667	12.61824	.178	-7.5241	59.8574
2.00	1.00	-49.91667*	12.61824	.002	-83.6074	-16.2259
	3.00	-92.41667*	12.61824	.000	-126.1074	-58.7259
	4.00	-23.75000	12.61824	.250	-57.4408	9.9408
3.00	1.00	42.50000*	12.61824	.008	8.8092	76.1908
	2.00	92.41667*	12.61824	.000	58.7259	126.1074
	4.00	68.66667*	12.61824	.000	34.9759	102.3574
4.00	1.00	-26.16667	12.61824	.178	-59.8574	7.5241
	2.00	23.75000	12.61824	.250	-9.9408	57.4408
	3.00	-68.66667*	12.61824	.000	-102.3574	-34.9759

*. The mean difference is significant at the 0.05 level.

Homogeneous Subsets

height2010

Tukey HSD[a]

Species	N	Subset for alpha = 0.05		
		1	2	3
2.00	12	107.0000		
4.00	12	130.7500	130.7500	
1.00	12		156.9167	
3.00	12			199.4167
Sig.		.250	.178	1.000

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 12.

For diameter species 3 was significantly different from normal even after LN transformation so non parametric Kruskal Wallis and Mann Whitney test were used.

Kruskal Wallis

Ranks

	Species	N	Mean Rank
diam2010	1.00	12	27.92
	2.00	11	18.18
	3.00	12	39.75
	4.00	12	9.67
	Total	47	

Test Statistics[a,b]

	diam2010
Chi-Square	31.907
df	3
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Species

Mann Whitney U tests

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2010	1.00	12	14.83	178.00
	2.00	11	8.91	98.00
	Total	23		

Test Statistics[a]

	diam2010
Mann-Whitney U	32.000
Wilcoxon W	98.000
Z	-2.093
Asymp. Sig. (2-tailed)	.036
Exact Sig. [2*(1-tailed Sig.)]	.037[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2010	1.00	12	8.25	99.00
	3.00	12	16.75	201.00
	Total	24		

Test Statistics[a]

	diam2010
Mann-Whitney U	21.000
Wilcoxon W	99.000
Z	-2.944
Asymp. Sig. (2-tailed)	.003
Exact Sig. [2*(1-tailed Sig.)]	.002[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2010	1.00	12	17.83	214.00
	4.00	12	7.17	86.00
	Total	24		

Test Statistics[a]

	diam2010
Mann-Whitney U	8.000
Wilcoxon W	86.000
Z	-3.695
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2010	2.00	11	6.00	66.00
	3.00	12	17.50	210.00
	Total	23		

Test Statistics[a]

	diam2010
Mann-Whitney U	.000
Wilcoxon W	66.000
Z	-4.062
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2010	2.00	11	15.27	168.00
	4.00	12	9.00	108.00
	Total	23		

Test Statistics[a]

	diam2010
Mann-Whitney U	30.000
Wilcoxon W	108.000
Z	-2.216
Asymp. Sig. (2-tailed)	.027
Exact Sig. [2*(1-tailed Sig.)]	.027[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2010	3.00	12	18.50	222.00
	4.00	12	6.50	78.00
	Total	24		

Test Statistics[a]

	diam2010
Mann-Whitney U	.000
Wilcoxon W	78.000
Z	-4.157
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Appendix 7.8 Comparison of stem volume by species after two growing seasons.

Species: 1 = Alder, 2 = Ash, 3= *E. gunnii*, 4= sycamore

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
vol2010	1.00	.218	12	.121	.912	12	.226
	2.00	.170	11	.200*	.938	11	.501
	3.00	.170	12	.200*	.932	12	.397
	4.00	.175	12	.200*	.903	12	.173

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Stem volume 2010 data were normally distributed so use a Levene's test to check equality of variances:

Test of Homogeneity of Variances

vol2010

Levene Statistic	df1	df2	Sig.
5.072	3	43	.004

So volume 2010 data were normal but showed inequality of variances. A Games Howell test can be used to detect differences between origins as it requires normality but is insensitive to inequality in variances:

Multiple Comparisons

Dependent Variable: vol2010 Games-Howell

(I) Species	(J) Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1.00	2.00	5.56902*	1.76541	.027	.5476	10.5905
	3.00	-8.08333*	2.24303	.008	-14.3129	-1.8538
	4.00	6.30583*	1.66831	.009	1.4751	11.1366
2.00	1.00	-5.56902*	1.76541	.027	-10.5905	-.5476
	3.00	-13.65235*	1.82997	.000	-18.8716	-8.4331
	4.00	.73682	1.04922	.895	-2.2178	3.6915
3.00	1.00	8.08333*	2.24303	.008	1.8538	14.3129
	2.00	13.65235*	1.82997	.000	8.4331	18.8716
	4.00	14.38917*	1.73648	.000	9.3483	19.4300
4.00	1.00	-6.30583*	1.66831	.009	-11.1366	-1.4751
	2.00	-.73682	1.04922	.895	-3.6915	2.2178
	3.00	-14.38917*	1.73648	.000	-19.4300	-9.3483

*. The mean difference is significant at the 0.05 level.

Appendix 7.9 Comparison of diameter, height and volume by species after three growing seasons.

1 = Alder, 2 = Ash, 3= E. gunnii, 4= sycamore

Tests of Normality[c,d,e,f,g,h]

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Species	Statistic	df	Sig.	Statistic	df	Sig.
diam2011	1.00	.130	12	.200*	.953	12	.682
	2.00	.106	12	.200*	.969	12	.899
	4.00	.197	12	.200*	.930	12	.379
height2011	1.00	.288	12	.007	.792	12	.008
	2.00	.180	12	.200*	.904	12	.181
	4.00	.134	12	.200*	.953	12	.684
LNheight2011	1.00	.227	12	.088	.878	12	.082
	2.00	.217	12	.123	.953	12	.677
	4.00	.136	12	.200*	.953	12	.674
vol2011	1.00	.317	12	.002	.792	12	.008
	2.00	.199	12	.200*	.869	12	.063
	4.00	.203	12	.186	.929	12	.365
LNvol2011	1.00	.198	12	.200*	.946	12	.576
	2.00	.176	12	.200*	.959	12	.770
	4.00	.135	12	.200*	.981	12	.986

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Diameter, LN height and LN volume all not significantly different from normal. Test equality of variances:

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
LNheight2011	.296	2	33	.745
LNvol2011	.529	2	33	.594
diam2011	3.367	2	33	.047

LN height and LN volume variances not significantly different so use an ANOVA and post hoc tests. For diameter use non parametric Kruskal Wallis and Mann Whitney tests.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LNheight2011	Between Groups	1.100	2	.550	7.272	.002
	Within Groups	2.495	33	.076		
	Total	3.595	35			
LNvol2011	Between Groups	6.507	2	3.253	9.177	.001
	Within Groups	11.699	33	.355		
	Total	18.205	35			

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) Species	(J) Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
LNheight2011	1.00	2.00	.42442*	.11226	.002	.1490	.6999
		4.00	.26078	.11226	.066	-.0147	.5362
	2.00	1.00	-.42442*	.11226	.002	-.6999	-.1490
		4.00	-.16364	.11226	.324	-.4391	.1118
	4.00	1.00	-.26078	.11226	.066	-.5362	.0147
		2.00	.16364	.11226	.324	-.1118	.4391
LNvol2011	1.00	2.00	.89365*	.24307	.002	.2972	1.4901
		4.00	.90983*	.24307	.002	.3134	1.5063
	2.00	1.00	-.89365*	.24307	.002	-1.4901	-.2972
		4.00	.01618	.24307	.998	-.5803	.6126
	4.00	1.00	-.90983*	.24307	.002	-1.5063	-.3134
		2.00	-.01618	.24307	.998	-.6126	.5803

*. The mean difference is significant at the 0.05 level.

Homogenous subsets:

LNheight2011

Tukey HSD[a]

Species	N	Subset for alpha = 0.05 1	2
2.00	12	4.8785	
4.00	12	5.0422	5.0422
1.00	12		5.3029
Sig.		.324	.066

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 12.000.

LNvol2011

Tukey HSD[a]

Species	N	Subset for alpha = 0.05 1	2
4.00	12	2.1581	
2.00	12	2.1743	
1.00	12		3.0679
Sig.		.998	1.000

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 12.000.

Kruskal Wallis (diameter)

Ranks

	Species	N	Mean Rank
diam2011	1.00	12	27.67
	2.00	12	16.75
	4.00	12	11.08
	Total	36	

Test Statistics[a,b]

	diam2011
Chi-Square	15.362
df	2
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Species

Mann Whitney

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2011	1.00	12	16.42	197.00
	2.00	12	8.58	103.00
	Total	24		

Test Statistics[a]

	diam2011
Mann-Whitney U	25.000
Wilcoxon W	103.000
Z	-2.714
Asymp. Sig. (2-tailed)	.007
Exact Sig. [2*(1-tailed Sig.)]	.006[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2011	1.00	12	17.75	213.00
	4.00	12	7.25	87.00
	Total	24		

Test Statistics[a]

	diam2011
Mann-Whitney U	9.000
Wilcoxon W	87.000
Z	-3.637
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
diam2011	2.00	12	14.67	176.00
	4.00	12	10.33	124.00
	Total	24		

Test Statistics[a]

	diam2011
Mann-Whitney U	46.000
Wilcoxon W	124.000
Z	-1.501
Asymp. Sig. (2-tailed)	.133
Exact Sig. [2*(1-tailed Sig.)]	.143[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Appendix 7.10 Comparison of stem volume, specific gravity and stem weight by species after two growing seasons.

Species: 1= ash, 2= alder, 3=sycamore, 4=*E. gunnii*

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Species	Statistic	df	Sig.	Statistic	df	Sig.
LNSpecgrav	1.00	.181	11	.200*	.917	11	.297
	2.00	.313	12	.002	.706	12	.001
	3.00	.141	12	.200*	.975	12	.954
	4.00	.161	12	.200*	.951	12	.654
Stemdrywt	1.00	.169	11	.200*	.939	11	.503
	2.00	.218	12	.121	.912	12	.226
	3.00	.174	12	.200*	.903	12	.173
	4.00	.170	12	.200*	.932	12	.397
Stemvol	1.00	.169	11	.200*	.939	11	.503
	2.00	.218	12	.121	.912	12	.226
	3.00	.174	12	.200*	.903	12	.173
	4.00	.170	12	.200*	.932	12	.397
Specgrav	1.00	.204	11	.200*	.882	11	.111
	2.00	.275	12	.013	.782	12	.006
	3.00	.127	12	.200*	.985	12	.997
	4.00	.130	12	.200*	.961	12	.796

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Stemdrywt	5.090	3	43	.004
Stemvol	5.069	3	43	.004

Specific gravity, species 2 is distributed significantly differently from normal even when LN transformed. For stem dry weight and stem volume data is normal but variances are different. As such a non parametric approach has been adopted using a Kruskal Wallis test followed by Mann Whitney tests to compare pairs of species:

Kruskal Wallis test:

Ranks

	Species	N	Mean Rank
Specgrav	1.00	15	41.47
	2.00	15	9.20
	3.00	15	32.80
	4.00	15	38.53
	Total	60	
Stemvol	1.00	11	14.82
	2.00	12	28.42
	3.00	12	12.33
	4.00	12	39.67
	Total	47	
Stemdrywt	1.00	11	18.09
	2.00	12	23.08
	3.00	12	13.25
	4.00	12	41.08
	Total	47	

Test Statistics[a,b]

	Specgrav	Stemvol	Stemdrywt
Chi-Square	31.661	30.533	28.101
df	3	3	3
Asymp. Sig.	.000	.000	.000

a. Kruskal Wallis Test
b. Grouping Variable: Species

Mann Whitney tests between pairs of species:

Ranks

	Species	N	Mean Rank	Sum of Ranks
Specgrav	1.00	15	23.00	345.00
	2.00	15	8.00	120.00
	Total	30		
Stemvol	1.00	11	8.00	88.00
	2.00	12	15.67	188.00
	Total	23		
Stemdrywt	1.00	11	10.45	115.00
	2.00	12	13.42	161.00
	Total	23		

Test Statistics[a]

	Specgrav	Stemvol	Stemdrywt
Mann-Whitney U	.000	22.000	49.000
Wilcoxon W	120.000	88.000	115.000
Z	-4.666	-2.708	-1.046
Asymp. Sig. (2-tailed)	.000	.007	.295
Exact Sig. [2*(1-tailed Sig.)]	.000[b]	.006[b]	.316[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
Specgrav	1.00	15	18.67	280.00
	3.00	15	12.33	185.00

	Total	30		
Stemvol	1.00	11	12.82	141.00
	3.00	12	11.25	135.00
	Total	23		
Stemdrywt	1.00	11	13.64	150.00
	3.00	12	10.50	126.00
	Total	23		

Test Statistics[a]

	Specgrav	Stemvol	Stemdrywt
Mann-Whitney U	65.000	57.000	48.000
Wilcoxon W	185.000	135.000	126.000
Z	-1.970	-.554	-1.108
Asymp. Sig. (2-tailed)	.049	.580	.268
Exact Sig. [2*(1-tailed Sig.)]	.050[b]	.608[b]	.288[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
Specgrav	1.00	15	15.80	237.00
	4.00	15	15.20	228.00
	Total	30		
Stemvol	1.00	11	6.00	66.00
	4.00	12	17.50	210.00
	Total	23		
Stemdrywt	1.00	11	6.00	66.00
	4.00	12	17.50	210.00
	Total	23		

Test Statistics[a]

	Specgrav	Stemvol	Stemdrywt
Mann-Whitney U	108.000	.000	.000
Wilcoxon W	228.000	66.000	66.000
Z	-.187	-4.062	-4.062
Asymp. Sig. (2-tailed)	.852	.000	.000
Exact Sig. [2*(1-tailed Sig.)]	.870[b]	.000[b]	.000[b]

a. Grouping Variable: Species
b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
Specgrav	2.00	15	8.40	126.00
	3.00	15	22.60	339.00
	Total	30		
Stemvol	2.00	12	17.42	209.00
	3.00	12	7.58	91.00
	Total	24		
Stemdrywt	2.00	12	15.75	189.00
	3.00	12	9.25	111.00
	Total	24		

Test Statistics[a]

	Specgrav	Stemvol	Stemdrywt
Mann-Whitney U	6.000	13.000	33.000

Wilcoxon W	126.000	91.000	111.000
Z	-4.417	-3.406	-2.252
Asymp. Sig. (2-tailed)	.000	.001	.024
Exact Sig. [2*(1-tailed Sig.)]	.000[b]	.000[b]	.024[b]

a. Grouping Variable: Species

b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
Specgrav	2.00	15	8.80	132.00
	4.00	15	22.20	333.00
	Total	30		
Stemvol	2.00	12	8.33	100.00
	4.00	12	16.67	200.00
	Total	24		
Stemdrywt	2.00	12	6.92	83.00
	4.00	12	18.08	217.00
	Total	24		

Test Statistics[a]

	Specgrav	Stemvol	Stemdrywt
Mann-Whitney U	12.000	22.000	5.000
Wilcoxon W	132.000	100.000	83.000
Z	-4.169	-2.887	-3.868
Asymp. Sig. (2-tailed)	.000	.004	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]	.003[b]	.000[b]

a. Grouping Variable: Species

b. Not corrected for ties.

Ranks

	Species	N	Mean Rank	Sum of Ranks
Specgrav	3.00	15	13.87	208.00
	4.00	15	17.13	257.00
	Total	30		
Stemvol	3.00	12	6.50	78.00
	4.00	12	18.50	222.00
	Total	24		
Stemdrywt	3.00	12	6.50	78.00
	4.00	12	18.50	222.00
	Total	24		

Test Statistics[a]

	Specgrav	Stemvol	Stemdrywt
Mann-Whitney U	88.000	.000	.000
Wilcoxon W	208.000	78.000	78.000
Z	-1.016	-4.157	-4.157
Asymp. Sig. (2-tailed)	.310	.000	.000
Exact Sig. [2*(1-tailed Sig.)]	.325[b]	.000[b]	.000[b]

a. Grouping Variable: Species, b. Not corrected for ties.

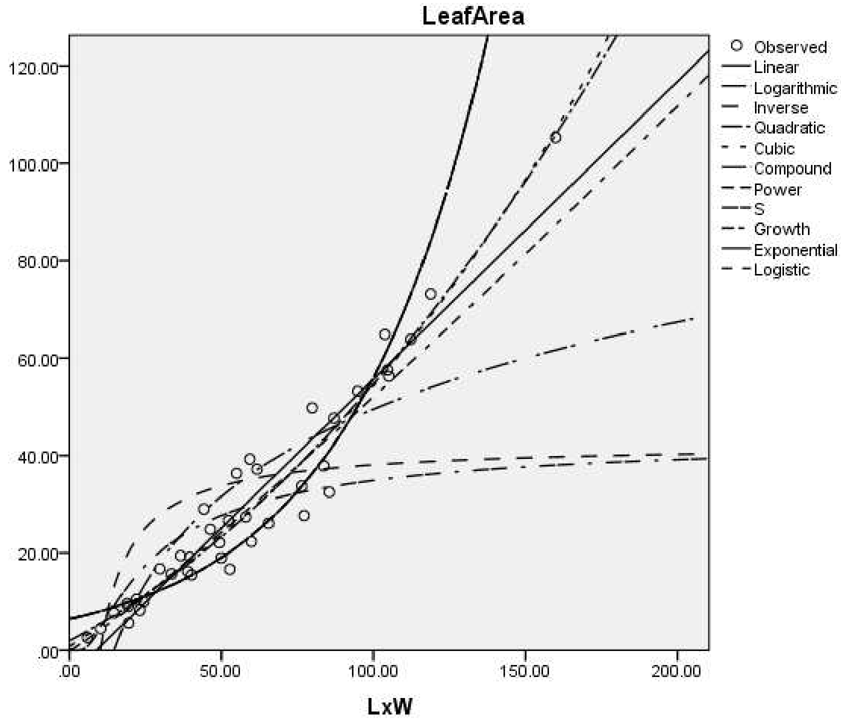
Appendix 7.11 Curve fitting for Alder LxW vs leaf area

Model Summary and Parameter Estimates

Dependent Variable: LeafArea , except Compound, Power, S, Growth, Exponential where is Ln(LeafArea) and Logistic where is Ln(1/LeafArea)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.923	453.922	1	38	.000	-5.408	.611		
Logarithmic	.708	92.124	1	38	.000	-69.352	25.812		
Inverse	.336	19.264	1	38	.000	42.410	-431.950		
Quadratic	.943	305.537	2	37	.000	1.989	.325	.002	
Cubic	.943	199.055	3	36	.000	.829	.399	.001	4.804E-6
Compound	.839	198.138	1	38	.000	6.478	1.022		
Power	.941	601.595	1	38	.000	.325	1.102		
S	.703	89.779	1	38	.000	3.783	-23.122		
Growth	.839	198.138	1	38	.000	1.868	.022		
Exponential	.839	198.138	1	38	.000	6.478	.022		
Logistic	.839	198.138	1	38	.000	.154	.979		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.961	.923	.921	6.207

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.841	.708	.700	12.069

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.580	.336	.319	18.193

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.971	.943	.940	5.408

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.971	.943	.938	5.471

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.916	.839	.835	.332

The independent variable is LxW. The dependent variable is ln(LeafArea).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.970	.941	.939	.202

The independent variable is LxW. The dependent variable is ln(LeafArea).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.838	.703	.695	.451

The independent variable is LxW. The dependent variable is ln(LeafArea).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.916	.839	.835	.332

The independent variable is LxW. The dependent variable is ln(LeafArea).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.916	.839	.835	.332

The independent variable is LxW. The dependent variable is ln(LeafArea).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.916	.839	.835	.332

The independent variable is LxW. The dependent variable is ln(LeafArea).

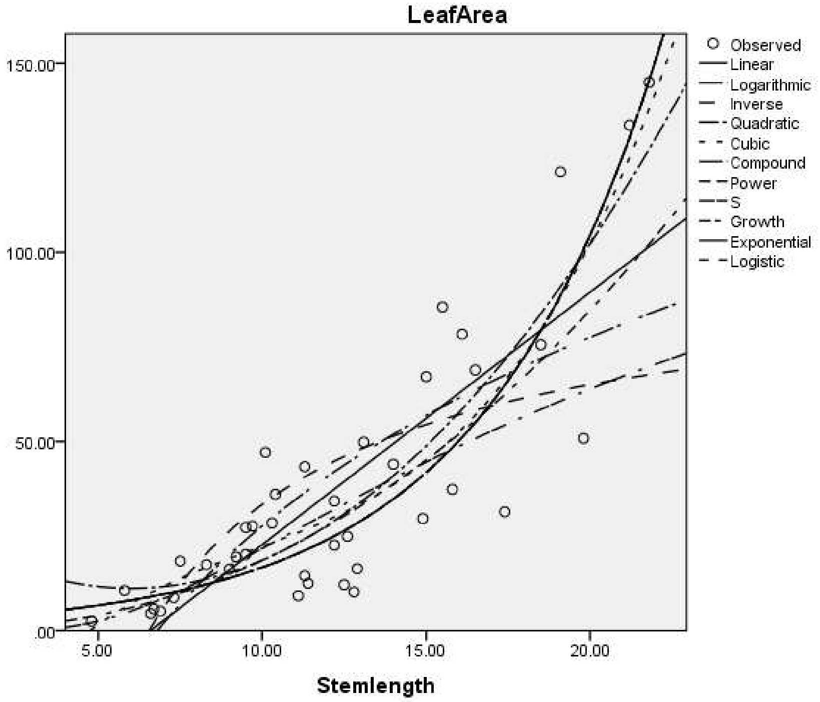
Appendix 7.12 Curve fitting for ash Leaf stem length vs leaf area

Model Summary and Parameter Estimates

Dependent Variable: LeafArea , except Compound, Power, S, Growth, Exponential where is Ln(LeafArea) and Logistic where is Ln(1/LeafArea)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.673	78.343	1	38	.000	-44.045	6.676		
Logarithmic	.567	49.748	1	38	.000	-138.040	71.968		
Inverse	.434	29.097	1	38	.000	96.728	-633.898		
Quadratic	.751	55.687	2	37	.000	27.971	-5.593	.466	
Cubic	.764	38.943	3	36	.000	-50.375	15.696	-1.283	.044
Compound	.685	82.682	1	38	.000	2.665	1.201		
Power	.707	91.524	1	38	.000	.120	2.189		
S	.677	79.697	1	38	.000	5.236	-21.582		
Growth	.685	82.682	1	38	.000	.980	.183		
Exponential	.685	82.682	1	38	.000	2.665	.183		
Logistic	.685	82.682	1	38	.000	.375	.832		

The independent variable is Stemlength.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.821	.673	.665	20.301

The independent variable is Stemlength.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.753	.567	.556	23.376

The independent variable is Stemlength.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.659	.434	.419	26.733

The independent variable is Stemlength.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.866	.751	.737	17.977

The independent variable is Stemlength.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.874	.764	.745	17.713

The independent variable is Stemlength.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.828	.685	.677	.543

The independent variable is Stemlength. The dependent variable is ln(LeafArea).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.841	.707	.699	.524

The independent variable is Stemlength. The dependent variable is ln(LeafArea).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.823	.677	.669	.550

The independent variable is Stemlength. The dependent variable is ln(LeafArea).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.828	.685	.677	.543

The independent variable is Stemlength. The dependent variable is ln(LeafArea).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.828	.685	.677	.543

The independent variable is Stemlength. The dependent variable is ln(LeafArea).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.828	.685	.677	.543

The independent variable is Stemlength. The dependent variable is ln(1 / LeafArea).

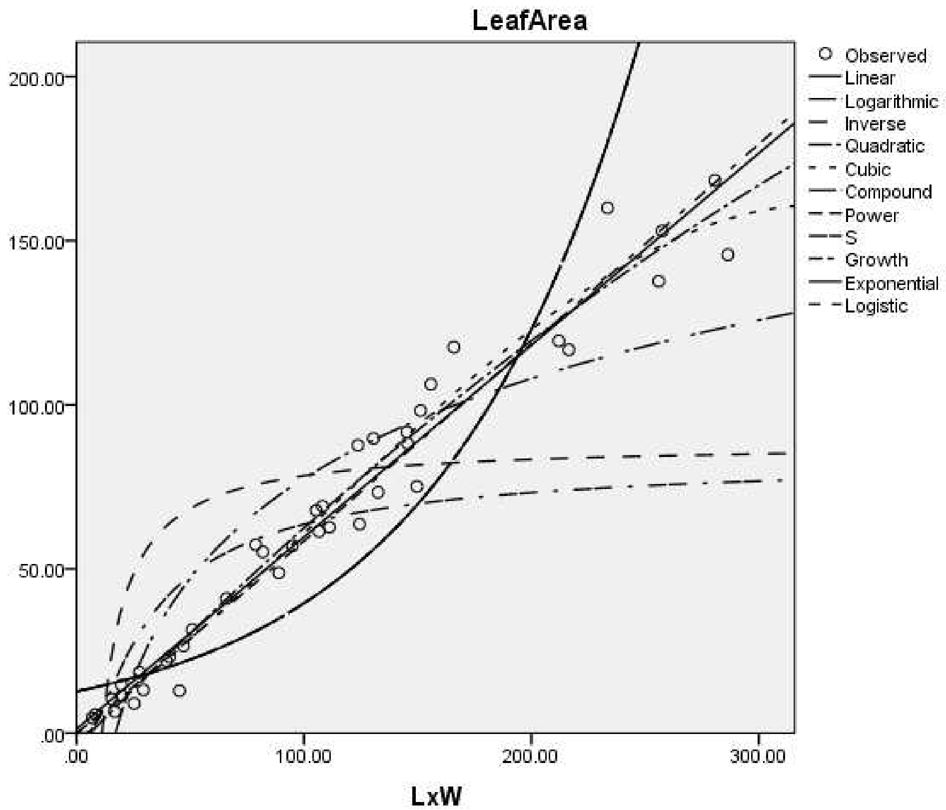
Appendix 7.13 Curve fitting for Sycamore LxW vs leaf area

Model Summary and Parameter Estimates

Dependent Variable: LeafArea , except Compound, Power, S, Growth, Exponential where is Ln(LeafArea) and Logistic where is Ln(1/LeafArea)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.964	1007.266	1	38	.000	1.236	.585		
Logarithmic	.819	171.803	1	38	.000	-124.938	43.967		
Inverse	.401	25.457	1	38	.000	88.353	-998.156		
Quadratic	.968	561.564	2	37	.000	-4.261	.716	.000	
Cubic	.970	382.622	3	36	.000	.034	.512	.001	-4.519E-6
Compound	.794	146.323	1	38	.000	12.705	1.011		
Power	.964	1022.992	1	38	.000	.532	1.021		
S	.700	88.706	1	38	.000	4.435	-28.206		
Growth	.794	146.323	1	38	.000	2.542	.011		
Exponential	.794	146.323	1	38	.000	12.705	.011		
Logistic	.794	146.323	1	38	.000	.079	.989		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.982	.964	.963	9.281

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.905	.819	.814	20.717

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.633	.401	.385	37.670

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.984	.968	.966	8.810

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.985	.970	.967	8.721

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.891	.794	.788	.473

The independent variable is LxW.The dependent variable is ln(LeafArea).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.982	.964	.963	.197

The independent variable is LxW.The dependent variable is ln(LeafArea).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.837	.700	.692	.570

The independent variable is LxW.The dependent variable is ln(LeafArea).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.891	.794	.788	.473

The independent variable is LxW.The dependent variable is ln(LeafArea).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.891	.794	.788	.473

The independent variable is LxW.The dependent variable is ln(LeafArea).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.891	.794	.788	.473

The independent variable is LxW.

The independent variable is LxW.The dependent variable is ln(1/LeafArea).

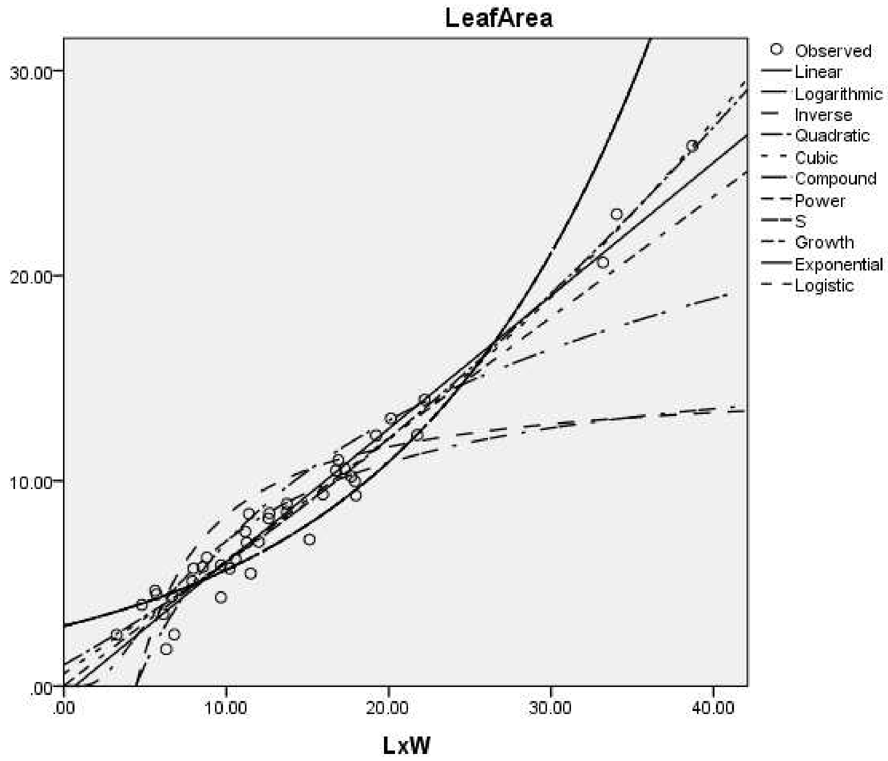
Appendix 7.14 Curve fitting for mature *E. gunnii* LxW vs leaf area

Model Summary and Parameter Estimates

Dependent Variable: LeafArea , except Compound, Power, S, Growth, Exponential where is Ln(LeafArea) and Logistic where is Ln(1/LeafArea)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.961	948.827	1	38	.000	-.439	.649		
Logarithmic	.802	153.530	1	38	.000	-12.777	8.585		
Inverse	.513	40.105	1	38	.000	14.995	-66.849		
Quadratic	.969	577.905	2	37	.000	1.032	.448	.005	
Cubic	.969	376.900	3	36	.000	.608	.545	-.001	.000
Compound	.824	178.340	1	38	.000	2.929	1.068		
Power	.877	271.425	1	38	.000	.633	.984		
S	.714	94.747	1	38	.000	2.820	-8.637		
Growth	.824	178.340	1	38	.000	1.075	.066		
Exponential	.824	178.340	1	38	.000	2.929	.066		
Logistic	.824	178.340	1	38	.000	.341	.936		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.981	.961	.960	1.042

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.895	.802	.796	2.364

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.717	.513	.501	3.702

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.984	.969	.967	.947

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.984	.969	.967	.958

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.908	.824	.820	.244

The independent variable is LxW. The dependent variable is ln(LeafArea).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.937	.877	.874	.204

The independent variable is LxW. The dependent variable is ln(LeafArea).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.845	.714	.706	.311

The independent variable is LxW. The dependent variable is ln(LeafArea).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.908	.824	.820	.244

The independent variable is LxW. The dependent variable is ln(LeafArea).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.908	.824	.820	.244

The independent variable is LxW. The dependent variable is ln(LeafArea).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.908	.824	.820	.244

The independent variable is LxW. The dependent variable is ln(1/LeafArea).

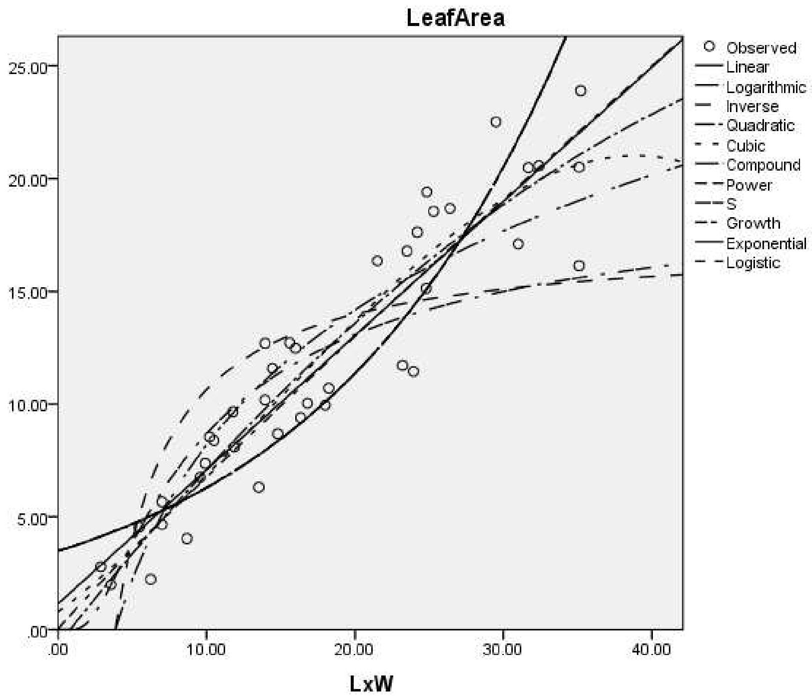
Appendix 7.15 Curve fitting for juvenile *E. gunnii* LxW vs leaf area

Model Summary and Parameter Estimates

Dependent Variable: LeafArea , except Compound, Power, S, Growth, Exponential where is Ln(LeafArea) and Logistic where is Ln(1/LeafArea)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.869	251.066	1	38	.000	1.144	.595		
Logarithmic	.818	170.548	1	38	.000	-11.690	8.634		
Inverse	.558	47.973	1	38	.000	17.337	-67.037		
Quadratic	.876	130.932	2	37	.000	-.676	.838	-.006	
Cubic	.878	86.504	3	36	.000	.781	.499	.014	.000
Compound	.777	132.140	1	38	.000	3.485	1.061		
Power	.884	290.076	1	38	.000	.771	.943		
S	.755	116.894	1	38	.000	2.981	-8.189		
Growth	.777	132.140	1	38	.000	1.249	.059		
Exponential	.777	132.140	1	38	.000	3.485	.059		
Logistic	.777	132.140	1	38	.000	.287	.943		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.932	.869	.865	2.194

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.904	.818	.813	2.583

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.747	.558	.546	4.024

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.936	.876	.870	2.158

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.937	.878	.868	2.170

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.771	.300

The independent variable is LxW. The dependent variable is ln(LeafArea).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.940	.884	.881	.216

The independent variable is LxW. The dependent variable is ln(LeafArea).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.869	.755	.748	.315

The independent variable is LxW. The dependent variable is ln(LeafArea).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.771	.300

The independent variable is LxW. The dependent variable is ln(LeafArea).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.771	.300

The independent variable is LxW. The dependent variable is ln(LeafArea).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.771	.300

The independent variable is LxW. The dependent variable is ln(1/LeafArea).

Appendix 7.16 Comparison of number of leaves by species

1=Alder, 2=ash, 3=*E. gunnii*, 4=sycamore

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
LNNleaves	1.00	.169	12	.200*	.956	12	.728
	2.00	.095	12	.200*	.979	12	.980
	3.00	.212	12	.143	.829	12	.021
	4.00	.205	12	.177	.909	12	.205
Nleaves	1.00	.269	12	.016	.813	12	.013
	2.00	.212	12	.142	.845	12	.032
	3.00	.302	12	.004	.640	12	.000
	4.00	.320	12	.001	.754	12	.003

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.

The data for species 3 (*E. gunnii*) was not normally distributed even after a LN transformation and so a non parametric approach was used, a Kruskal Wallis test followed by Mann Whitney tests.

Kruskal Wallis test:

Ranks

	Species	N	Mean Rank
Nleaves	1.00	12	28.42
	2.00	12	12.96
	3.00	12	42.33
	4.00	12	14.29
	Total	48	

Test Statistics[a,b]

	Nleaves
Chi-Square	34.956
df	3
Asymp. Sig.	.000

a. Kruskal Wallis Test
b. Grouping Variable: Species

Highly significant differences so investigate using Mann Whitney tests:

Ranks

	Species	N	Mean Rank	Sum of Ranks
Nleaves	1.00	12	17.50	210.00
	2.00	12	7.50	90.00
	Total	24		

Test Statistics[b]

	Nleaves
Mann-Whitney U	12.000
Wilcoxon W	90.000
Z	-3.464
Asymp. Sig. (2-tailed)	.001
Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

Ranks

	Species	N	Mean Rank	Sum of Ranks
Nleaves	1.00	12	6.67	80.00
	3.00	12	18.33	220.00
	Total	24		

Test Statistics[b]

	Nleaves
Mann-Whitney U	2.000
Wilcoxon W	80.000
Z	-4.041
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

Ranks

	Species	N	Mean Rank	Sum of Ranks
Nleaves	1.00	12	17.25	207.00
	4.00	12	7.75	93.00
	Total	24		

Test Statistics[b]

	Nleaves
Mann-Whitney U	.000
Wilcoxon W	78.000
Z	-4.157
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

Ranks

	Species	N	Mean Rank	Sum of Ranks
Nleaves	2.00	12	11.96	143.50
	4.00	12	13.04	156.50
	Total	24		

Test Statistics[b]

	Nleaves
Mann-Whitney U	65.500
Wilcoxon W	143.500
Z	-.376
Asymp. Sig. (2-tailed)	.707
Exact Sig. [2*(1-tailed Sig.)]	.713[a]

a. Not corrected for ties.
b. Grouping Variable: Species

Ranks

	Species	N	Mean Rank	Sum of Ranks
Nleaves	3.00	12	18.50	222.00
	4.00	12	6.50	78.00
	Total	24		

Test Statistics[b]

	Nleaves
Mann-Whitney U	.000
Wilcoxon W	78.000
Z	-4.161
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

Ranks

	Species	N	Mean Rank	Sum of Ranks
Nleaves	2.00	12	6.50	78.00
	3.00	12	18.50	222.00
	Total	24		

Test Statistics[b]

	Nleaves
Mann-Whitney U	.000
Wilcoxon W	78.000
Z	-4.157
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

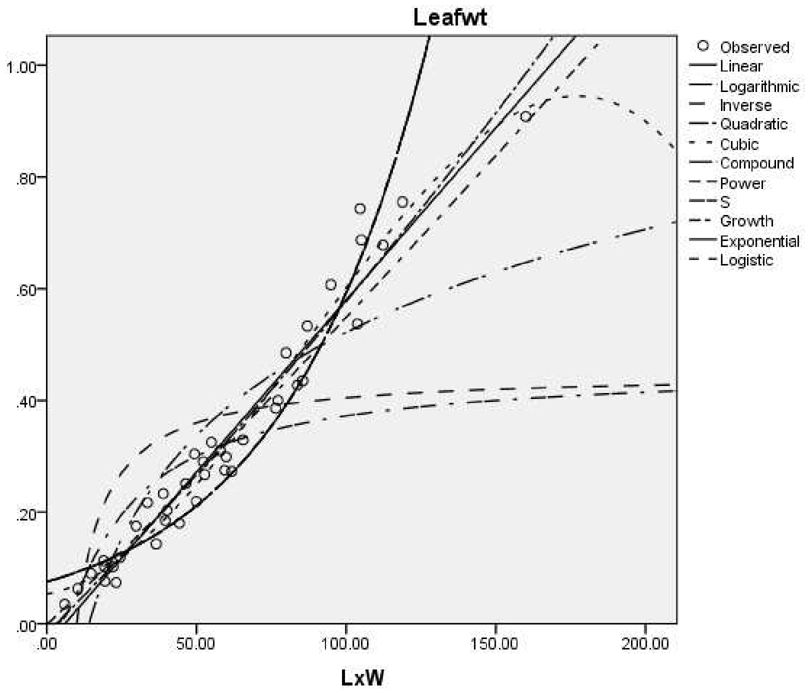
Appendix 7.17 Curve fitting for alder LxW vs leaf weight

Model Summary and Parameter Estimates

Dependent Variable: Leafwt , except Compound, Power, S, Growth, Exponential where is Ln(Leafwt) and Logistic where is Ln(1/Leafwt)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.956	835.396	1	38	.000	-.036	.006		
Logarithmic	.766	124.659	1	38	.000	-.703	.266		
Inverse	.370	22.288	1	38	.000	.449	-4.484		
Quadratic	.958	421.263	2	37	.000	-.017	.005	5.363E-6	
Cubic	.967	349.369	3	36	.000	.054	.001	7.512E-5	-2.921E-7
Compound	.866	245.928	1	38	.000	.075	1.021		
Power	.955	800.320	1	38	.000	.004	1.044		
S	.683	82.058	1	38	.000	-.774	-21.449		
Growth	.866	245.928	1	38	.000	-2.585	.021		
Exponential	.866	245.928	1	38	.000	.075	.021		
Logistic	.866	245.928	1	38	.000	13.260	.980		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.978	.956	.955	.046

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.875	.766	.760	.107

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.608	.370	.353	.176

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.979	.958	.956	.046

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.983	.967	.964	.041

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.931	.866	.863	.285

The independent variable is LxW. The dependent variable is ln(Leafwt).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.977	.955	.953	.166

The independent variable is LxW. The dependent variable is ln(Leafwt).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.827	.683	.675	.438

The independent variable is LxW. The dependent variable is ln(Leafwt).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.931	.866	.863	.285

The independent variable is LxW. The dependent variable is ln(Leafwt).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.931	.866	.863	.285

The independent variable is LxW. The dependent variable is ln(Leafwt).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.931	.866	.863	.285

The independent variable is LxW. The dependent variable is ln(1 / Leafwt)

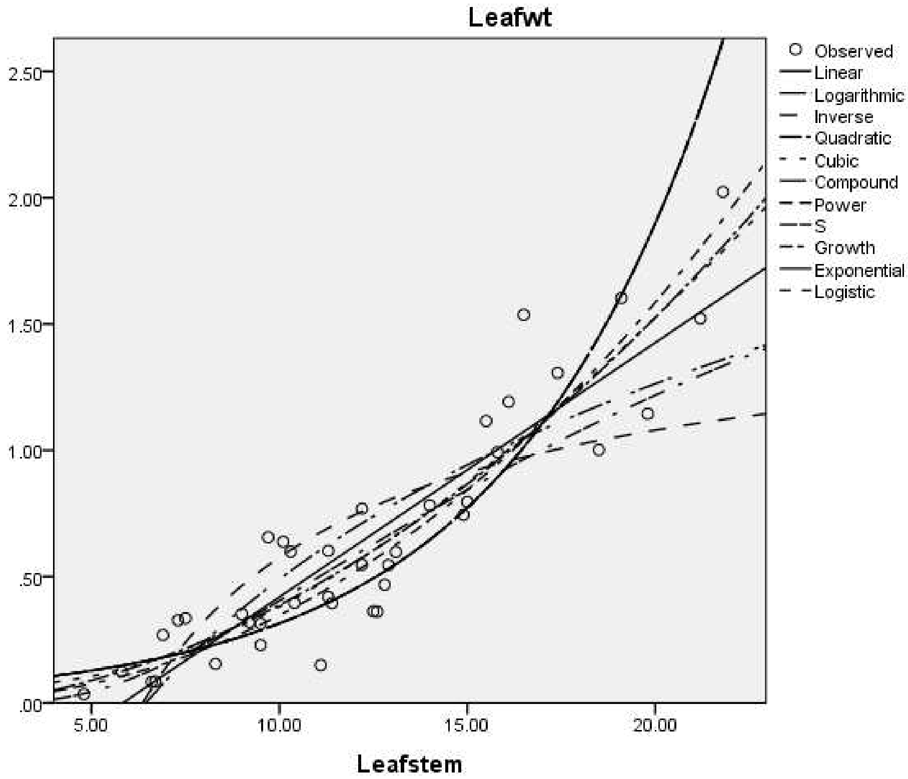
Appendix 7.18 Curve fitting for ash Leaf stem length vs leaf weight

Model Summary and Parameter Estimates

Dependent Variable: Leafwt , except Compound, Power, S, Growth, Exponential where is Ln(Leafwt) and Logistic where is Ln(1/Leafwt)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.828	183.171	1	38	.000	-.588	.101		
Logarithmic	.737	106.640	1	38	.000	-2.080	1.116		
Inverse	.593	55.351	1	38	.000	1.584	-10.080		
Quadratic	.853	107.637	2	37	.000	-.029	.005	.004	
Cubic	.854	69.938	3	36	.000	.104	-.031	.007	-7.449E-5
Compound	.752	115.534	1	38	.000	.052	1.197		
Power	.811	163.272	1	38	.000	.002	2.192		
S	.809	161.075	1	38	.000	1.300	-22.049		
Growth	.752	115.534	1	38	.000	-2.953	.180		
Exponential	.752	115.534	1	38	.000	.052	.180		
Logistic	.752	115.534	1	38	.000	19.160	.836		

The independent variable is Leafstem.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.910	.828	.824	.200

The independent variable is Leafstem.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.859	.737	.730	.248

The independent variable is Leafstem.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.770	.593	.582	.308

The independent variable is Leafstem.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.924	.853	.845	.187

The independent variable is Leafstem.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.924	.854	.841	.190

The independent variable is Leafstem.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.867	.752	.746	.450

The independent variable is Leafstem. The dependent variable is ln(Leafwt).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.901	.811	.806	.393

The independent variable is Leafstem. The dependent variable is ln(Leafwt).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.900	.809	.804	.395

The independent variable is Leafstem. The dependent variable is ln(Leafwt).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.867	.752	.746	.450

The independent variable is Leafstem. The dependent variable is ln(Leafwt).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.867	.752	.746	.450

The independent variable is Leafstem. The dependent variable is ln(Leafwt).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.867	.752	.746	.450

The independent variable is Leafstem. The dependent variable is ln(1/Leafwt).

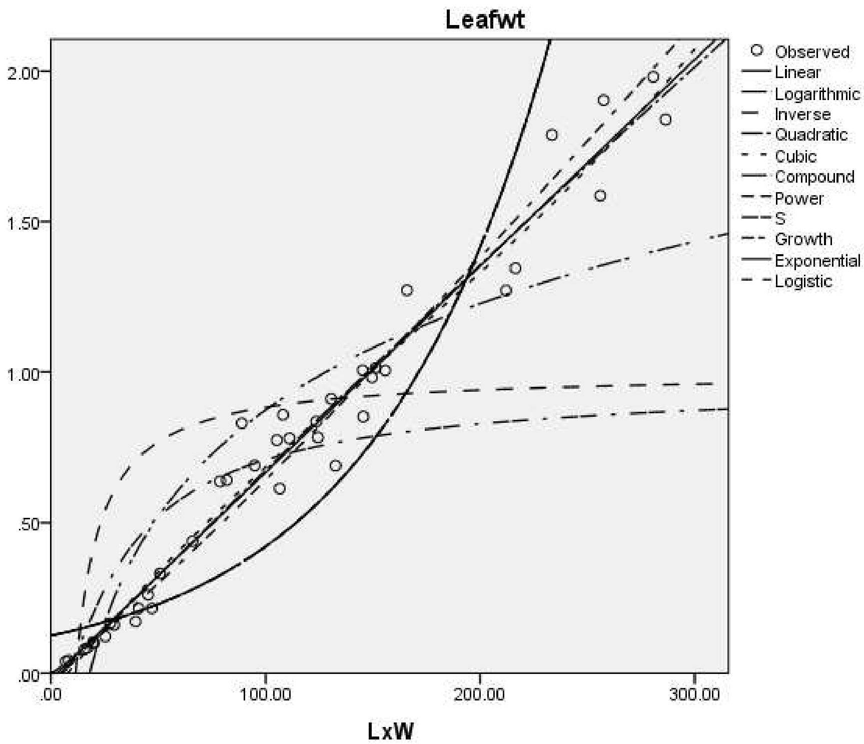
Appendix 7.19 Curve fitting for Sycamore LxW vs leaf weight

Model Summary and Parameter Estimates

Dependent Variable: Leafwt , except Compound, Power, S, Growth, Exponential where is Ln(Leafwt) and Logistic where is Ln(1/Leafwt)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.970	1214.664	1	38	.000	-.020	.007		
Logarithmic	.805	156.858	1	38	.000	-1.474	.510		
Inverse	.391	24.380	1	38	.000	.998	-11.522		
Quadratic	.970	595.742	2	37	.000	-.034	.007	-1.248E-6	
Cubic	.970	394.707	3	36	.000	-.066	.009	-1.552E-5	3.397E-8
Compound	.788	141.486	1	38	.000	.125	1.012		
Power	.983	2260.080	1	38	.000	.004	1.106		
S	.744	110.603	1	38	.000	-.033	-31.203		
Growth	.788	141.486	1	38	.000	-2.080	.012		
Exponential	.788	141.486	1	38	.000	.125	.012		
Logistic	.788	141.486	1	38	.000	8.006	.988		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.985	.970	.969	.099

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.897	.805	.800	.251

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.625	.391	.375	.444

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.985	.970	.968	.100

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.985	.970	.968	.100

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.888	.788	.783	.514

The independent variable is LxW. The dependent variable is ln(Leafwt).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.992	.983	.983	.144

The independent variable is LxW. The dependent variable is ln(Leafwt).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.863	.744	.738	.565

The independent variable is LxW.

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.888	.788	.783	.514

The independent variable is LxW.

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.888	.788	.783	.514

The independent variable is LxW.

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.888	.788	.783	.514

The independent variable is LxW.

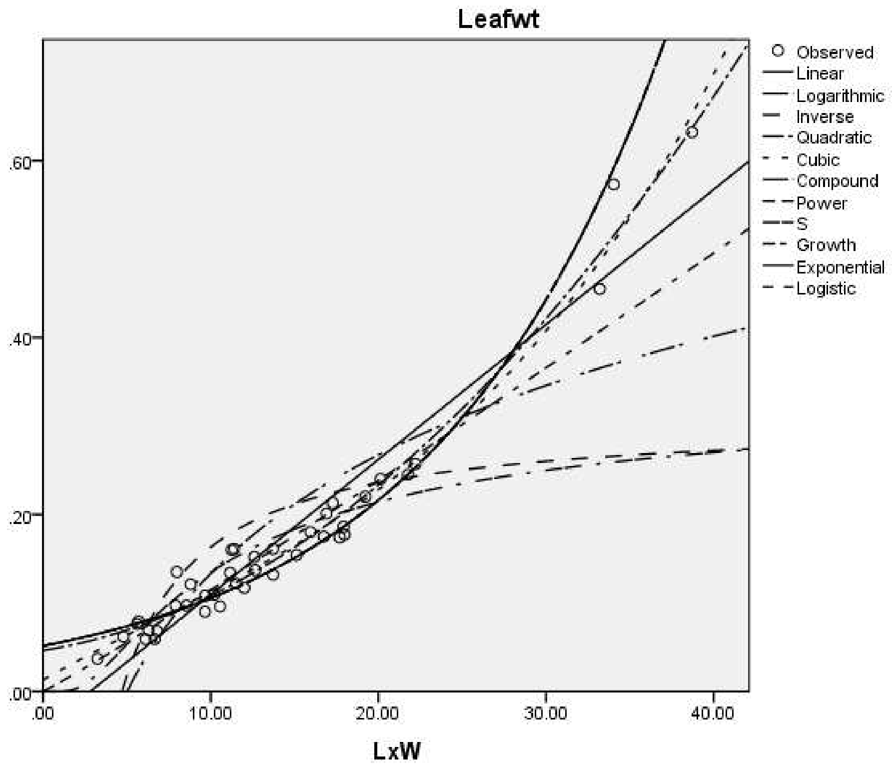
Appendix 7.20 Curve fitting for *E. gunnii* mature LxW vs leaf weight

Model Summary and Parameter Estimates

Dependent Variable: Leafwt , except Compound, Power, S, Growth, Exponential where is Ln(Leafwt) and Logistic where is Ln(1/Leafwt)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.925	467.726	1	38	.000	-.043	.015		
Logarithmic	.708	92.102	1	38	.000	-.312	.194		
Inverse	.423	27.898	1	38	.000	.309	-1.456		
Quadratic	.973	664.644	2	37	.000	.046	.003	.000	
Cubic	.975	461.570	3	36	.000	.013	.011	.000	7.865E-6
Compound	.902	349.238	1	38	.000	.051	1.074		
Power	.928	492.319	1	38	.000	.010	1.055		
S	.761	120.833	1	38	.000	-1.077	-9.293		
Growth	.902	349.238	1	38	.000	-2.967	.072		
Exponential	.902	349.238	1	38	.000	.051	.072		
Logistic	.902	349.238	1	38	.000	19.443	.931		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.962	.925	.923	.035

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.841	.708	.700	.069

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.651	.423	.408	.097

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.986	.973	.971	.021

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.987	.975	.973	.021

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.950	.902	.899	.190

The independent variable is LxW. The dependent variable is ln(Leafwt).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.964	.928	.926	.162

The independent variable is LxW. The dependent variable is ln(Leafwt).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.872	.761	.754	.297

The independent variable is LxW. The dependent variable is ln(Leafwt).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.950	.902	.899	.190

The independent variable is LxW. The dependent variable is ln(Leafwt).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.950	.902	.899	.190

The independent variable is LxW. The dependent variable is ln(Leafwt).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.950	.902	.899	.190

The independent variable is LxW. The dependent variable is ln(1/Leafwt).

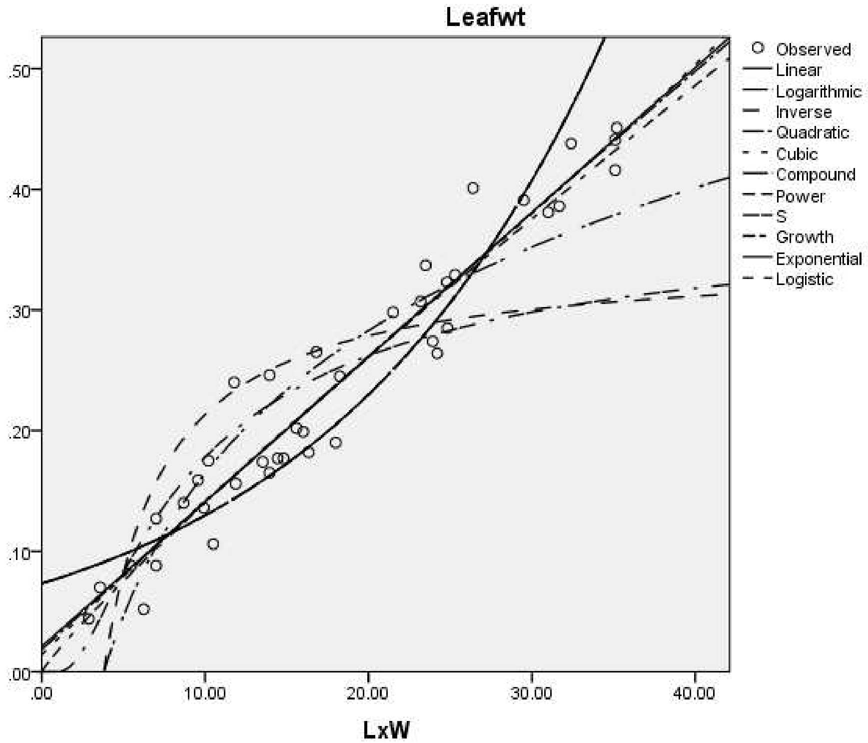
Appendix 7.21 Curve fitting for *E. gunnii* juvenile LxW vs leaf weight

Model Summary and Parameter Estimates

Dependent Variable: Leafwt , except Compound, Power, S, Growth, Exponential where is Ln(Leafwt) and Logistic where is Ln(1/Leafwt)

	Model Summary					Parameter Estimates			
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.934	533.826	1	38	.000	.021	.012		
Logarithmic	.845	207.334	1	38	.000	-.228	.171		
Inverse	.562	48.708	1	38	.000	.344	-1.308		
Quadratic	.934	260.059	2	37	.000	.018	.012	-8.832E-6	
Cubic	.934	168.808	3	36	.000	.014	.013	-6.890E-5	1.037E-6
Compound	.832	188.623	1	38	.000	.073	1.059		
Power	.915	407.800	1	38	.000	.018	.897		
S	.771	127.655	1	38	.000	-.952	-7.743		
Growth	.832	188.623	1	38	.000	-2.615	.057		
Exponential	.832	188.623	1	38	.000	.073	.057		
Logistic	.832	188.623	1	38	.000	13.662	.944		

The independent variable is LxW.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.966	.934	.932	.030

The independent variable is LxW.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.919	.845	.841	.046

The independent variable is LxW.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.749	.562	.550	.078

The independent variable is LxW.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.966	.934	.930	.031

The independent variable is LxW.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.966	.934	.928	.031

The independent variable is LxW.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.912	.832	.828	.244

The independent variable is LxW. The dependent variable is ln(Leafwt).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.956	.915	.913	.174

The independent variable is LxW. The dependent variable is ln(Leafwt).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.878	.771	.765	.285

The independent variable is LxW. The dependent variable is ln(Leafwt).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.912	.832	.828	.244

The independent variable is LxW. The dependent variable is ln(Leafwt).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.912	.832	.828	.244

The independent variable is LxW. The dependent variable is ln(Leafwt).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.912	.832	.828	.244

The independent variable is LxW. The dependent variable is ln(1/Leafwt).

Appendix 7.22 Leaf area, leaf weight, growing season analysis by species and block

SPECIES

1=Alder, 2=sycamore, 3=ash, 4=Egunnii

Leafweight, leafarea, growing season

Tests of Normality(b)

	Species	Kolmogorov-Smirnov(a) Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Lweight	1.00	.252	12	.034	.808	12	.012
	2.00	.177	12	.200(*)	.932	12	.398
	3.00	.271	11	.023	.797	11	.009
	4.00	.310	12	.002	.752	12	.003
LArea	1.00	.275	12	.013	.806	12	.011
	2.00	.210	12	.151	.907	12	.193
	3.00	.272	11	.022	.794	11	.008
	4.00	.291	12	.006	.768	12	.004
Growseas	1.00	.136	12	.200(*)	.971	12	.922
	2.00	.218	12	.120	.920	12	.283
	3.00	.194	11	.200(*)	.970	11	.891

* This is a lower bound of the true significance.
a Lilliefors Significance Correction
b Growseas is constant when Species = 4.00. It has been omitted.

Only growing season was normally distributed for all species so test equality of variances for growing season:.

Variances for Grow season

Test of Homogeneity of Variances

Growseason

Levene Statistic	df1	df2	Sig.
.073	2	32	.929

Growing season variances not different so use an ANOVA and Tukey's test

ANOVA

Growseason

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	150874.937	2	75437.468	26.555	.000
Within Groups	90905.949	32	2840.811		
Total	241780.886	34			

Multiple Comparisons

Dependent Variable: Growseason

Tukey HSD

(I) Species	(J) Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
1.00	2.00	141.62500*	21.75933	.000	88.1542	195.0958
	3.00	134.43182*	22.24837	.000	79.7593	189.1043
2.00	1.00	-141.62500*	21.75933	.000	-195.0958	-88.1542
	3.00	-7.19318	22.24837	.944	-61.8657	47.4793
3.00	1.00	-134.43182*	22.24837	.000	-189.1043	-79.7593
	2.00	7.19318	22.24837	.944	-47.4793	61.8657

*. The mean difference is significant at the 0.05 level.

Growseason

Tukey HSD[a,b]

Species	N	Subset for alpha = 0.05 1	2
2.00	12	875.6250	
3.00	11	882.8182	
1.00	12		1017.2500
Sig.		.943	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 11.647.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

For all other variables use a Kruskal Wallis test:

Ranks

	Species	N	Mean Rank
Lweight	1.00	12	23.50
	2.00	12	19.17
	3.00	12	14.42
	4.00	12	40.92
	Total	48	
LArea	1.00	12	27.00
	2.00	12	19.33
	3.00	12	12.75
	4.00	12	38.92
	Total	48	

Test Statistics(a,b)

	Lweight	LArea
Chi-Square	24.528	23.195
df	3	3
Asymp. Sig.	.000	.000

a Kruskal Wallis Test
b Grouping Variable: Species

Results of Mann Whitney U tests (p values)

Lweight

	1	2	3	4
1		.478	.068	.000
2			.266	.000
3				.000
4				

LArea

	1	2	3	4
1		.266	0.01	0.052
2			0.089	0.000
3				.000
4				

Volume 2010, LAxGS

Tests of Normality

		Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Species	Statistic	df	Sig.	Statistic	df	Sig.
Vol10	1.00	.218	12	.121	.912	12	.226
	2.00	.174	12	.200(*)	.903	12	.173
	3.00	.162	10	.200(*)	.931	10	.459
	4.00	.170	12	.200(*)	.932	12	.397
LAxGS	1.00	.290	12	.006	.796	12	.009
	2.00	.242	12	.051	.882	12	.094
	3.00	.301	10	.011	.721	10	.002
	4.00	.291	12	.006	.768	12	.004

* This is a lower bound of the true significance.
a Lilliefors Significance Correction

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Vol10	5.069	3	43	.004
LAxGS	5.938	3	43	.002

So a Kruskal Wallis test is appropriate for both variables

Ranks

	Species	N	Mean Rank
LAxGS	1.00	12	25.75
	2.00	12	17.75
	3.00	11	12.27
	4.00	12	39.25
	Total	47	
Vol10	1.00	12	28.42
	2.00	12	12.33
	3.00	11	14.82
	4.00	12	39.67
	Total	47	

Test Statistics(a,b)

	LAxGS	Vol10
Chi-Square	25.580	30.533
df	3	3
Asymp. Sig.	.000	.000

a Kruskal Wallis Test
b Grouping Variable: Species

Vol2010

	1	2	3	4
1		0.000	0.006	.003
2			0.608	.000
3				.000
4				

LAxGS

	1	2	3	4
1		.143	0.011	.007
2			0.169	.000
3				.000
4				

BLOCKS

Tests of Normality

	Block	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Vol10	1.00	.227	8	.200(*)	.901	8	.296
	2.00	.284	7	.092	.847	7	.117
	3.00	.322	8	.015	.737	8	.006
	4.00	.234	8	.200(*)	.876	8	.174
	5.00	.352	7	.009	.754	7	.014
	6.00	.239	8	.198	.850	8	.096
LAxGS	1.00	.248	8	.161	.889	8	.228
	2.00	.309	7	.042	.733	7	.008
	3.00	.361	8	.003	.606	8	.000
	4.00	.345	8	.006	.778	8	.017
	5.00	.374	7	.004	.751	7	.013
	6.00	.234	8	.200(*)	.879	8	.185
Lweight	1.00	.212	8	.200(*)	.883	8	.201
	2.00	.317	7	.032	.732	7	.008
	3.00	.371	8	.002	.599	8	.000
	4.00	.271	8	.085	.841	8	.077
	5.00	.275	7	.117	.817	7	.061
	6.00	.213	8	.200(*)	.864	8	.132
LArea	1.00	.204	8	.200(*)	.912	8	.371
	2.00	.251	7	.200(*)	.792	7	.034
	3.00	.327	8	.012	.641	8	.000
	4.00	.321	8	.015	.845	8	.085
	5.00	.299	7	.057	.842	7	.103
	6.00	.199	8	.200(*)	.911	8	.364
Growseas	1.00	.327	8	.012	.714	8	.003
	2.00	.240	7	.200(*)	.818	7	.061
	3.00	.265	8	.103	.784	8	.019
	4.00	.280	8	.064	.773	8	.015
	5.00	.304	7	.049	.756	7	.015
	6.00	.270	8	.089	.834	8	.065

* This is a lower bound of the true significance.
a Lilliefors Significance Correction

None follow a normal distribution by block

KW test:

Test Statistics(a,b)

	LAxGS	Vol10	Lweight	LArea	Growseas
Chi-Square	1.075	.998	1.240	1.524	.279
df	5	5	5	5	5
Asymp. Sig.	.956	.963	.941	.910	.998

a Kruskal Wallis Test
b Grouping Variable: Block

Appendix 7.23 LAR and SLA by species and by block

By species
1=Alder, 2=sycamore, 3=ash, 4 =*E. gunni*
Test of normality

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
LAR	1.00	.197	12	.200*	.899	12	.155
	2.00	.202	12	.192	.885	12	.101
	3.00	.319	12	.001	.699	12	.001
	4.00	.226	12	.091	.787	12	.007
SLA	1.00	.365	12	.000	.677	12	.001
	2.00	.452	12	.000	.597	12	.000
	3.00	.100	12	.200*	.977	12	.966
	4.00	.137	12	.200*	.953	12	.688

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.

After LN transformation

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
LNLAR	1.00	.145	12	.200*	.939	12	.483
	2.00	.191	12	.200*	.906	12	.188
	3.00	.296	12	.005	.771	12	.004
	4.00	.152	12	.200*	.899	12	.156
LNSLA	1.00	.350	12	.000	.710	12	.001
	2.00	.453	12	.000	.600	12	.000
	3.00	.103	12	.200*	.972	12	.932
	4.00	.145	12	.200*	.944	12	.557

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.

The data even after LN transformation were not normally distributed so a Kruskal Wallis test and Mann Whitney tests were used to identify differences in LAR and SLA between species:

Ranks

	Species	N	Mean Rank
LAR	1.00	12	29.42
	2.00	12	30.33
	3.00	12	10.50
	4.00	12	27.75
	Total	48	
SLA	1.00	12	39.42
	2.00	12	27.92
	3.00	12	18.17
	4.00	12	12.50
	Total	48	

Test Statistics[a,b]

	LAR	SLA
Chi-Square	16.210	25.610
df	3	3
Asymp. Sig.	.001	.000

a. Kruskal Wallis Test
b. Grouping Variable: Species

MWU LAR

1 & 2

Ranks

	Species	N	Mean Rank	Sum of Ranks
LAR	1.00	12	12.50	150.00
	2.00	12	12.50	150.00
	Total	24		

Test Statistics[b]

	LAR
Mann-Whitney U	72.000
Wilcoxon W	150.000
Z	.000
Asymp. Sig. (2-tailed)	1.000
Exact Sig. [2*(1-tailed Sig.)]	1.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

1 & 3

Ranks

	Species	N	Mean Rank	Sum of Ranks
LAR	1.00	12	15.33	184.00
	3.00	11	8.36	92.00
	Total	23		

Test Statistics[a]

	LAR
Mann-Whitney U	26.000
Wilcoxon W	92.000
Z	-2.462
Asymp. Sig. (2-tailed)	.014
Exact Sig. [2*(1-tailed Sig.)]	.013[b]

a. Grouping Variable: Species
b. Not corrected for ties.

1 & 4

Ranks

	Species	N	Mean Rank	Sum of Ranks
LAR	1.00	12	12.75	153.00
	4.00	12	12.25	147.00
	Total	24		

Test Statistics[b]

	LAR
Mann-Whitney U	69.000
Wilcoxon W	147.000
Z	-.173
Asymp. Sig. (2-tailed)	.862
Exact Sig. [2*(1-tailed Sig.)]	.887[a]

a. Not corrected for ties.
b. Grouping Variable: Species

2 & 3

Ranks

	Species	N	Mean Rank	Sum of Ranks
LAR	2.00	12	15.75	189.00
	3.00	11	7.91	87.00
	Total	23		

Test Statistics[a]

	LAR
Mann-Whitney U	21.000
Wilcoxon W	87.000
Z	-2.770
Asymp. Sig. (2-tailed)	.006
Exact Sig. [2*(1-tailed Sig.)]	.004[b]

a. Grouping Variable: Species
b. Not corrected for ties.

2 & 4

Ranks

	Species	N	Mean Rank	Sum of Ranks
LAR	2.00	12	13.75	165.00
	4.00	12	11.25	135.00
	Total	24		

Test Statistics[b]

	LAR
Mann-Whitney U	57.000
Wilcoxon W	135.000
Z	-.866
Asymp. Sig. (2-tailed)	.386
Exact Sig. [2*(1-tailed Sig.)]	.410[a]

a. Not corrected for ties.
b. Grouping Variable: Species

3 & 4

Ranks

	Species	N	Mean Rank	Sum of Ranks
LAR	3.00	11	8.18	90.00
	4.00	12	15.50	186.00
	Total	23		

Test Statistics[a]

	LAR
Mann-Whitney U	24.000
Wilcoxon W	90.000
Z	-2.585
Asymp. Sig. (2-tailed)	.010
Exact Sig. [2*(1-tailed Sig.)]	.009[b]

a. Grouping Variable: Species
b. Not corrected for ties.

MWU SLA

1 & 2

Ranks

	Species	N	Mean Rank	Sum of Ranks
SLA	1.00	12	15.42	185.00
	2.00	12	9.58	115.00
	Total	24		

Test Statistics[b]

	SLA
Mann-Whitney U	37.000
Wilcoxon W	115.000
Z	-2.021
Asymp. Sig. (2-tailed)	.043
Exact Sig. [2*(1-tailed Sig.)]	.045[a]

a. Not corrected for ties.
b. Grouping Variable: Species

1 & 3

Ranks

	Species	N	Mean Rank	Sum of Ranks
SLA	1.00	12	18.50	222.00
	3.00	12	6.50	78.00
	Total	24		

Test Statistics[a]

	SLA
Mann-Whitney U	.000
Wilcoxon W	78.000
Z	-4.157
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]

a. Grouping Variable: Species
b. Not corrected for ties.

1 & 4

Ranks

	Species	N	Mean Rank	Sum of Ranks
SLA	1.00	12	18.50	222.00
	4.00	12	6.50	78.00
	Total	24		

Test Statistics[b]

	SLA
Mann-Whitney U	.000
Wilcoxon W	78.000
Z	-4.157
Asymp. Sig. (2-tailed)	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[a]

a. Not corrected for ties.
b. Grouping Variable: Species

2 & 3

Ranks

	Species	N	Mean Rank	Sum of Ranks
SLA	2.00	12	15.58	187.00
	3.00	12	9.42	113.00
	Total	24		

Test Statistics[a]

	SLA
Mann-Whitney U	35.000
Wilcoxon W	113.000
Z	-2.136
Asymp. Sig. (2-tailed)	.033
Exact Sig. [2*(1-tailed Sig.)]	.033[b]

a. Grouping Variable: Species
b. Not corrected for ties.

2 & 4

Ranks

	Species	N	Mean Rank	Sum of Ranks
SLA	2.00	12	15.75	189.00
	4.00	12	9.25	111.00
	Total	24		

Test Statistics[b]

	SLA
Mann-Whitney U	33.000
Wilcoxon W	111.000
Z	-2.252
Asymp. Sig. (2-tailed)	.024
Exact Sig. [2*(1-tailed Sig.)]	.024[a]

a. Not corrected for ties.
b. Grouping Variable: Species

3 & 4

Ranks

	Species	N	Mean Rank	Sum of Ranks
SLA	3.00	12	15.25	183.00
	4.00	12	9.75	117.00
	Total	24		

Test Statistics[a]

	SLA
Mann-Whitney U	39.000
Wilcoxon W	117.000
Z	-1.905
Asymp. Sig. (2-tailed)	.057
Exact Sig. [2*(1-tailed Sig.)]	.060[b]

a. Grouping Variable: Species
b. Not corrected for ties.

By Block

Ranks

	Block	N	Mean Rank
LAR	1.00	8	24.50
	2.00	8	22.75
	3.00	8	26.63
	4.00	8	23.75
	5.00	8	20.00
	6.00	8	29.38
	Total	48	
SLA	1.00	8	22.75
	2.00	8	20.13
	3.00	8	23.63
	4.00	8	26.50
	5.00	8	27.13
	6.00	8	26.88
	Total	48	

Test Statistics[a,b]

	LAR	SLA
Chi-Square	2.129	1.612
df	5	5
Asymp. Sig.	.831	.900

a. Kruskal Wallis Test
b. Grouping Variable: Block

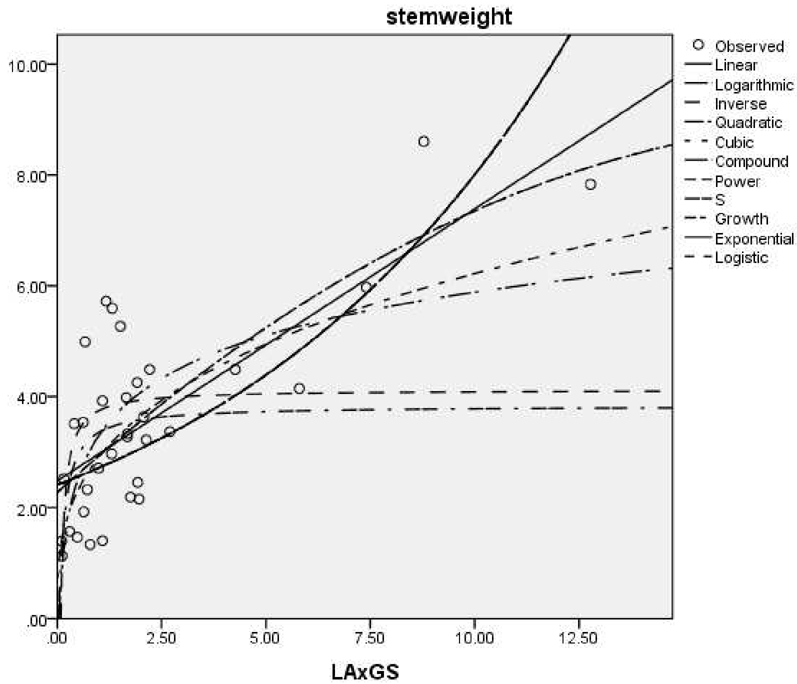
Appendix 7.24: Curve fitting of Stem weight vs growth potential index

Model Summary and Parameter Estimates

Dependent Variable: Stemweight , except Compound, Power, S, Growth, Exponential where is Ln(Stemweight) and Logistic where is Ln(1/Stemweight)

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.548	38.815	1	32	.000	2.479	.491		
Logarithmic	.483	29.918	1	32	.000	3.299	1.123		
Inverse	.220	9.009	1	32	.005	4.126	-.378		
Quadratic	.557	19.495	2	31	.000	2.267	.683	-.017	
Cubic	.557	12.578	3	30	.000	2.267	.684	-.018	1.145E-5
Compound	.391	20.568	1	32	.000	2.410	1.128		
Power	.498	31.804	1	32	.000	2.908	.330		
S	.320	15.089	1	32	.000	1.343	-.132		
Growth	.391	20.568	1	32	.000	.880	.120		
Exponential	.391	20.568	1	32	.000	2.410	.120		
Logistic	.391	20.568	1	32	.000	.415	.887		

The independent variable is LAxGS.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.740	.548	.534	1.226

The independent variable is LAxGS.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.695	.483	.467	1.311

The independent variable is LAxGS.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.469	.220	.195	1.611

The independent variable is LAxGS.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.746	.557	.529	1.233

The independent variable is LAxGS.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.746	.557	.513	1.253

The independent variable is LAxGS.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.626	.391	.372	.412

The independent variable is LAxGS. The dependent variable is ln(stemweight).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.706	.498	.483	.374

The independent variable is LAxGS. The dependent variable is ln(stemweight).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.566	.320	.299	.435

The independent variable is LAxGS. The dependent variable is ln(stemweight).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.626	.391	.372	.412

The independent variable is LAxGS. The dependent variable is ln(stemweight).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.626	.391	.372	.412

The independent variable is LAxGS. The dependent variable is ln(stemweight).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.626	.391	.372	.412

The independent variable is LAxGS. The dependent variable is ln(1/stemweight).

Appendix 7.25 Comparison of types of frost damage between *E. nitens* and *E. gunnii*.

1=*E. nitens*, 2 = *E. gunnii*

Tests of Normality

	Species	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
frostlow	1.00	.133	123	.000	.910	123	.000
	2.00	.397	131	.000	.374	131	.000
frosthigh	1.00	.243	123	.000	.779	123	.000
	2.00	.487	131	.000	.196	131	.000
foliage	1.00	.256	123	.000	.844	123	.000
	2.00	.258	131	.000	.758	131	.000

a. Lilliefors Significance Correction

The data were not normal so to test if differences in the different forms of frost damage were significant between *E. nitens* and *E. gunnii* a Kolmogorov Smirnov test was used:

Frequencies

	Species	N
frostlow	1.00	144
	2.00	144
	Total	288
frosthigh	1.00	123
	2.00	131
	Total	254
foliage	1.00	144
	2.00	144
	Total	288

Test Statistics[a]

		frostlow	frosthigh	foliage
Most Extreme Differences	Absolute	.590	.478	.646
	Positive	.000	.478	.000
	Negative	-.590	-.007	-.646
Kolmogorov-Smirnov Z		5.009	3.803	5.480
Asymp. Sig. (2-tailed)		.000	.000	.000

a. Grouping Variable: Species

Appendix 7.26 *E. gunnii*, comparison of frost damage by quartile.

Quartiles: 1=smallest, 2=small, 3 = large, 4 = largest

Tests of Normality

	Quartile	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
frostlow	1.00	.382	35	.000	.546	35	.000
	2.00	.350	34	.000	.666	34	.000
	3.00	.526	35	.000	.318	35	.000
	4.00	.461	31	.000	.547	31	.000
frosthigh	1.00	.434	35	.000	.384	35	.000
	2.00	.538	34	.000	.255	34	.000
	3.00	.539	35	.000	.250	35	.000
	4.00	.539	31	.000	.176	31	.000
foliage	1.00	.257	35	.000	.812	35	.000
	2.00	.273	34	.000	.713	34	.000
	3.00	.272	35	.000	.773	35	.000
	4.00	.332	31	.000	.708	31	.000

a. Lilliefors Significance Correction

Data was highly significantly different from normal so a Kruskal Wallis test was used to identify significant differences between quartiles:

Ranks

	Quartile	N	Mean Rank
frostlow	1.00	35	73.97
	2.00	34	76.03
	3.00	35	56.01
	4.00	31	65.98
	Total	135	
frosthigh	1.00	35	75.71
	2.00	34	65.88
	3.00	35	65.77
	4.00	31	64.13
	Total	135	
foliage	1.00	35	83.03
	2.00	34	69.15
	3.00	35	61.04
	4.00	31	57.63
	Total	135	

Test Statistics[a,b]

	frostlow	frosthigh	foliage
Chi-Square	9.517	7.717	8.946
df	3	3	3
Asymp. Sig.	.023	.052	.030

a. Kruskal Wallis Test
b. Grouping Variable: Quartile

For low stem damage (frostlow) and foliage Mann Whitney tests were used to detect significant differences between pairs of quartiles:

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	1.00	35	34.90	1221.50
	2.00	34	35.10	1193.50
	Total	69		
foliage	1.00	35	38.67	1353.50
	2.00	34	31.22	1061.50
	Total	69		

Test Statistics[a]

	frostlow	foliage
Mann-Whitney U	591.500	466.500
Wilcoxon W	1221.500	1061.500
Z	-.050	-1.582
Asymp. Sig. (2-tailed)	.960	.114

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	1.00	35	39.79	1392.50
	3.00	35	31.21	1092.50
	Total	70		
foliage	1.00	35	41.10	1438.50
	3.00	35	29.90	1046.50
	Total	70		

Test Statistics[a]

	frostlow	foliage
Mann-Whitney U	462.500	416.500
Wilcoxon W	1092.500	1046.500
Z	-2.524	-2.341
Asymp. Sig. (2-tailed)	.012	.019

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	1.00	35	35.29	1235.00
	4.00	31	31.48	976.00
	Total	66		
foliage	1.00	35	39.26	1374.00
	4.00	31	27.00	837.00
	Total	66		

Test Statistics[a]

	frostlow	foliage
Mann-Whitney U	480.000	341.000
Wilcoxon W	976.000	837.000
Z	-1.009	-2.650
Asymp. Sig. (2-tailed)	.313	.008

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	2.00	34	40.29	1370.00
	3.00	35	29.86	1045.00
	Total	69		
foliage	2.00	34	37.15	1263.00
	3.00	35	32.91	1152.00
	Total	69		

Test Statistics[a]

	frostlow	foliage
Mann-Whitney U	415.000	522.000
Wilcoxon W	1045.000	1152.000
Z	-2.928	-.903
Asymp. Sig. (2-tailed)	.003	.367

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	2.00	34	35.63	1211.50
	4.00	31	30.11	933.50
	Total	65		
foliage	2.00	34	35.78	1216.50
	4.00	31	29.95	928.50
	Total	65		

Test Statistics[a]

	frostlow	foliage
Mann-Whitney U	437.500	432.500
Wilcoxon W	933.500	928.500
Z	-1.428	-1.300
Asymp. Sig. (2-tailed)	.153	.194

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	3.00	35	30.94	1083.00
	4.00	31	36.39	1128.00
	Total	66		
foliage	3.00	35	34.23	1198.00
	4.00	31	32.68	1013.00
	Total	66		

Test Statistics[a]

	frostlow	foliage
Mann-Whitney U	453.000	517.000
Wilcoxon W	1083.000	1013.000
Z	-1.779	-.339
Asymp. Sig. (2-tailed)	.075	.735

a. Grouping Variable: Quartile

Appendix 7.27 *E. nitens*, comparison of frost damage by quartile.

Quartiles: 1=smallest, 2=small, 3 = large, 4 = largest

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Quartile	Statistic	df	Sig.	Statistic	Df	Sig.
frostlow	1.00	.209	24	.008	.874	24	.006
	2.00	.145	36	.055	.943	36	.064
	3.00	.167	36	.013	.876	36	.001
	4.00	.196	27	.009	.843	27	.001
frosthigh	1.00	.193	24	.022	.869	24	.005
	2.00	.331	36	.000	.708	36	.000
	3.00	.311	36	.000	.730	36	.000
	4.00	.251	27	.000	.804	27	.000
foliage	1.00	.334	24	.000	.535	24	.000
	2.00	.257	36	.000	.854	36	.000
	3.00	.296	36	.000	.804	36	.000
	4.00	.177	27	.029	.941	27	.130

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Data was significantly different from normal so a Kruskal Wallis test was used to identify significant differences between quartiles:

Ranks

	Quartile	N	Mean Rank
frostlow	1.00	36	94.21
	2.00	36	60.94
	3.00	36	62.61
	4.00	27	49.65
	Total	135	
frosthigh	1.00	24	89.92
	2.00	36	51.22
	3.00	36	57.50
	4.00	27	57.56
	Total	123	
foliage	1.00	36	97.58
	2.00	36	57.56
	3.00	36	62.50
	4.00	27	49.81
	Total	135	

Test Statistics[a,b]

	frostlow	frosthigh	foliage
Chi-Square	24.241	20.783	31.316
df	3	3	3
Asymp. Sig.	.000	.000	.000

a. Kruskal Wallis Test
b. Grouping Variable: Quartile

For all variables Mann Whitney tests were used to detect significant differences between pairs of quartiles:

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	1.00	36	46.03	1657.00
	2.00	36	26.97	971.00
	Total	72		
frosthigh	1.00	24	41.31	991.50
	2.00	36	23.29	838.50
	Total	60		
foliage	1.00	36	47.31	1703.00
	2.00	36	25.69	925.00
	Total	72		

Test Statistics[a]

	frostlow	frosthigh	foliage
Mann-Whitney U	305.000	172.500	259.000
Wilcoxon W	971.000	838.500	925.000
Z	-3.893	-4.059	-4.591
Asymp. Sig. (2-tailed)	.000	.000	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	1.00	36	44.58	1605.00
	3.00	36	28.42	1023.00
	Total	72		
frosthigh	1.00	24	40.33	968.00
	3.00	36	23.94	862.00
	Total	60		
foliage	1.00	36	46.00	1656.00
	3.00	36	27.00	972.00
	Total	72		

Test Statistics[a]

	frostlow	frosthigh	foliage
Mann-Whitney U	357.000	196.000	306.000
Wilcoxon W	1023.000	862.000	972.000
Z	-3.312	-3.643	-4.080
Asymp. Sig. (2-tailed)	.001	.000	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	1.00	36	40.60	1461.50
	4.00	27	20.54	554.50
	Total	63		
frosthigh	1.00	24	33.27	798.50
	4.00	27	19.54	527.50
	Total	51		
foliage	1.00	36	41.28	1486.00
	4.00	27	19.63	530.00
	Total	63		

Test Statistics[a]

	frostlow	frosthigh	foliage
Mann-Whitney U	176.500	149.500	152.000
Wilcoxon W	554.500	527.500	530.000
Z	-4.338	-3.353	-4.848
Asymp. Sig. (2-tailed)	.000	.001	.000

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	2.00	36	36.13	1300.50
	3.00	36	36.88	1327.50
	Total	72		
frosthigh	2.00	36	34.49	1241.50
	3.00	36	38.51	1386.50
	Total	72		
foliage	2.00	36	35.19	1267.00
	3.00	36	37.81	1361.00
	Total	72		

Test Statistics[a]

	frostlow	frosthigh	foliage
Mann-Whitney U	634.500	575.500	601.000
Wilcoxon W	1300.500	1241.500	1267.000
Z	-.153	-.887	-.545
Asymp. Sig. (2-tailed)	.878	.375	.586

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	2.00	36	34.85	1254.50
	4.00	27	28.20	761.50
	Total	63		
frosthigh	2.00	36	30.44	1096.00
	4.00	27	34.07	920.00
	Total	63		
foliage	2.00	36	33.67	1212.00
	4.00	27	29.78	804.00
	Total	63		

Test Statistics[a]

	frostlow	frosthigh	foliage
Mann-Whitney U	383.500	430.000	426.000
Wilcoxon W	761.500	1096.000	804.000
Z	-1.434	-.845	-.850
Asymp. Sig. (2-tailed)	.152	.398	.395

a. Grouping Variable: Quartile

Ranks

	Quartile	N	Mean Rank	Sum of Ranks
frostlow	3.00	36	34.32	1235.50
	4.00	27	28.91	780.50
	Total	63		
frosthigh	3.00	36	32.04	1153.50
	4.00	27	31.94	862.50
	Total	63		
foliage	3.00	36	34.69	1249.00
	4.00	27	28.41	767.00
	Total	63		

Test Statistics[a]

	frostlow	frosthigh	foliage
Mann-Whitney U	402.500	484.500	389.000
Wilcoxon W	780.500	862.500	767.000
Z	-1.172	-.022	-1.376
Asymp. Sig. (2-tailed)	.241	.982	.169

a. Grouping Variable: Quartile

Appendix 7.28 *E. gunnii*, comparison of survival by quartile in May.

A Chi squared test was used to investigate if survival was significantly different in quartiles:

Quartile * Survival Crosstabulation

Count

		Survival		Total
		.00	1.00	
Quartile	1.00	23	12	35
	2.00	20	14	34
	3.00	22	13	35
	4.00	31	9	40
Total		96	48	144

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	3.297[a]	3	.348
Likelihood Ratio	3.410	3	.333
Linear-by-Linear Association	1.416	1	.234
N of Valid Cases	144		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 11.33.

Appendix 7.29 *E. gunnii*, comparison of frost damage by block.

Tests of Normality[b,c,d,e]

	Block	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
frostlow	1.00	.396	23	.000	.672	23	.000
	2.00	.348	20	.000	.645	20	.000
	3.00	.413	23	.000	.378	23	.000
	4.00	.530	22	.000	.332	22	.000
	5.00	.472	24	.000	.526	24	.000
	6.00	.389	23	.000	.572	23	.000
frosthigh	1.00	.499	23	.000	.463	23	.000
	2.00	.420	20	.000	.417	20	.000
	3.00	.509	23	.000	.264	23	.000
	5.00	.539	24	.000	.209	24	.000
foliage	1.00	.283	23	.000	.725	23	.000
	2.00	.277	20	.000	.760	20	.000
	3.00	.284	23	.000	.730	23	.000
	4.00	.233	22	.003	.856	22	.004
	5.00	.274	24	.000	.732	24	.000
	6.00	.249	23	.001	.799	23	.000

a. Lilliefors Significance Correction

Data was significantly different from normal so a Kruskal Wallis test was used to identify significant differences between blocks:

Ranks

	Block	N	Mean Rank
frostlow	1.00	23	72.50
	2.00	20	81.85
	3.00	23	64.96
	4.00	22	55.95
	5.00	24	64.08
	6.00	23	70.11
	Total	135	
frosthigh	1.00	23	73.48
	2.00	20	79.15
	3.00	23	67.96
	4.00	22	62.00
	5.00	24	64.75
	6.00	23	62.00
	Total	135	
foliage	1.00	23	64.89
	2.00	20	75.35
	3.00	23	75.17
	4.00	22	55.66
	5.00	24	63.48
	6.00	23	74.07
	Total	135	

Test Statistics[a,b]

	frostlow	frosthigh	foliage
Chi-Square	9.056	13.562	4.945
df	5	5	5
Asymp. Sig.	.107	.019	.423

a. Kruskal Wallis Test,

Appendix 7.30 *E. nitens*, comparison of frost damage by block.

Tests of Normality

	Block	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
frostlow	1.00	.208	21	.018	.872	21	.010
	2.00	.208	21	.018	.872	21	.010
	3.00	.216	19	.020	.823	19	.002
	4.00	.164	17	.200*	.960	17	.626
	5.00	.176	21	.089	.897	21	.030
	6.00	.176	24	.054	.918	24	.053
frosthigh	1.00	.308	21	.000	.705	21	.000
	2.00	.308	21	.000	.705	21	.000
	3.00	.270	19	.001	.810	19	.002
	4.00	.196	17	.081	.824	17	.004
	5.00	.220	21	.009	.804	21	.001
	6.00	.244	24	.001	.816	24	.001
foliage	1.00	.218	21	.010	.899	21	.034
	2.00	.216	21	.012	.906	21	.046
	3.00	.226	19	.012	.849	19	.006
	4.00	.335	17	.000	.728	17	.000
	5.00	.276	21	.000	.826	21	.002
	6.00	.273	24	.000	.769	24	.000

*. This is a lower bound of the true significance. a. Lilliefors Significance Correction

None of the variables were normally distributed so use a non-parametric Kruskal Wallis test to investigate if differences by block were significant:

Ranks

	Block	N	Mean Rank
frostlow	1.00	24	56.58
	2.00	24	56.58
	3.00	24	67.33
	4.00	18	86.67
	5.00	21	69.55
	6.00	24	76.15
	Total	135	
frosthigh	1.00	21	55.83
	2.00	21	55.83
	3.00	19	65.74
	4.00	17	70.24
	5.00	21	62.71
	6.00	24	63.38
	Total	123	
foliage	1.00	24	58.63
	2.00	24	58.29
	3.00	24	79.33
	4.00	18	65.64
	5.00	21	64.36
	6.00	24	80.71
	Total	135	

Test Statistics[a,b]

	frostlow	frosthigh	foliage
Chi-Square	9.378	2.643	8.068
df	5	5	5
Asymp. Sig.	.095	.755	.153

a. Kruskal Wallis Test, b. Grouping Variable: Block

Appendix 7.31 *E. gunnii*, comparison of survival by block in May.

A Chi squared test was used to investigate if survival was significantly different in blocks (1=survived, 0 = dead):

Block * Survival Crosstabulation

Count

		Survival		Total
		.00	1.00	
Block	1.00	19	5	24
	2.00	18	6	24
	3.00	11	13	24
	4.00	16	8	24
	5.00	16	8	24
	6.00	17	7	24
Total		97	47	144

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	7.360[a]	5	.195
Likelihood Ratio	7.159	5	.209
Linear-by-Linear Association	.325	1	.568
N of Valid Cases	144		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 7.83.

Appendix 8 Statistical supporting data for volume and growth of *E. gunnii*

Appendix 8.1: Regressions- Measured volume vs estimated volume

(1) Woodhorn all trees

(a) Measured vs Shell

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.978[a]	.957	.957	.00373

a. Predictors: (Constant), Shell

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.002	.000		8.536	.000
	Shell	1.185	.012	.978	102.555	.000

a. Dependent Variable: Actual

(b) Measured vs AFOCEL

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.978[a]	.957	.957	.00373

a. Predictors: (Constant), AFOCEL

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.007	.000		30.497	.000
	AFOCEL	.916	.009	.978	102.555	.000

a. Dependent Variable: Actual

(2) Woodhorn trees > 10cm

(a) Measured vs Shell

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.996[a]	.992	.992	.00127

a. Predictors: (Constant), Shell

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.004	.000		12.680	.000
	Shell	1.132	.009	.996	124.063	.000

a. Dependent Variable: Actual

(b) Measured vs AFOCEL

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.996[a]	.992	.992	.00127

a. Predictors: (Constant), AFOCEL

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.009	.000		28.161	.000
	AFOCEL	.875	.007	.996	124.063	.000

a. Dependent Variable: Actual

(3) Thoresby

(a) Measured vs Shell

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.988[a]	.975	.974	.01196

a. Predictors: (Constant), Shell

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.003	.004		.805	.429
	Shell	1.111	.037	.988	30.052	.000

a. Dependent Variable: Actual

(b) Measured vs AFOCEL

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.976[a]	.952	.950	.01662

a. Predictors: (Constant), AFOCEL

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.004	.006		.748	.462
	AFOCEL	.891	.042	.976	21.373	.000

a. Dependent Variable: Actual

(4) Glenbranter/ Chiddingfold trees

(a) Measured vs Shell

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.989[a]	.977	.975	.05884

a. Predictors: (Constant), Shell

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.023	.025		.900	.389
	Shell	1.191	.057	.989	20.759	.000

a. Dependent Variable: Actual

(b) Measured vs AFOCEL

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.989[a]	.977	.975	.05870

a. Predictors: (Constant), AFOCEL

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.028	.025		1.122	.288
	AFOCEL	.920	.044	.989	20.810	.000

a. Dependent Variable: Actual

Appendix 8.2 Curve fitting for historic data: height vs age

Gompertz

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	24.245	2.171	19.805	28.685
B	2.700	.324	2.037	3.363
C	.124	.027	.068	.180

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3428.296	3	1142.765
Residual	218.272	29	7.527
Uncorrected Total	3646.568	32	
Corrected Total	1836.053	31	

Dependent variable: Height

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .881.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 2.743

Exponential

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	35.282	4.859	25.344	45.219
B	14.929	4.483	5.762	24.097
C	3.593	1.753	.007	7.179

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3476.572	3	1158.857
Residual	169.996	29	5.862
Uncorrected Total	3646.568	32	
Corrected Total	1836.053	31	

Dependent variable: Height

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .907.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 2.384

Richard's

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	43.160	23.502	-4.907	91.227
B	.022	.023	-.026	.069
C	.851	.161	.522	1.180

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3483.636	3	1161.212
Residual	162.932	29	5.618
Uncorrected Total	3646.568	32	
Corrected Total	1836.053	31	

Dependent variable: Height

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .911.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 2.370

Korf

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	4.723	.719	3.253	6.194
B	.818	4179057.897	-8547132.270	8547133.906
C	-.057	291173.604	-595516.943	595516.829

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3164.303	3	1054.768
Residual	482.265	29	16.630
Uncorrected Total	3646.568	32	
Corrected Total	1836.053	31	

Dependent variable: Height
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .737.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 4.078

Appendix 8.3 Curve fitting for historic data: dbh vs height

Model Description

Model Name		MOD_1
Dependent Variable	1	Dbh
Equation	1	Linear
	2	Logarithmic
	3	Inverse
	4	Quadratic
	5	Cubic
	6	Compound[a]
	7	Power[a]
	8	S[a]
	9	Growth[a]
	10	Exponential[a]
	11	Logistic[a]
Independent Variable		Height
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified
Tolerance for Entering Terms in Equations		.0001

Case Processing Summary

	N
Total Cases	15
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

.

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.918	.843	.831	3.181

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
height	1.044	.125	.918	8.357	.000
(Constant)	.797	1.901		.419	.682

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.872	.761	.743	3.924

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
ln(height)	14.055	2.183	.872	6.437	.000
(Constant)	-20.160	5.574		-3.617	.003

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.782	.611	.581	5.005

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
1 / height	-145.141	32.095	-.782	-4.522	.001
(Constant)	28.201	3.167		8.905	.000

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.922	.850	.826	3.231

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
height	.611	.574	.538	1.064	.308
height ** 2	.013	.017	.390	.773	.455
(Constant)	3.756	4.289		.876	.398

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.924	.854	.814	3.338

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
height	1.829	2.529	1.608	.723	.485
height ** 2	-.065	.158	-1.963	-.411	.689
height ** 3	.001	.003	1.331	.495	.630
(Constant)	-1.704	11.880		-.143	.889

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.880	.775	.757	.241

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	1.065	.010	2.411	105.596	.000
(Constant)	5.670	.817		6.940	.000

The dependent variable is ln(dbh).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.877	.770	.752	.244

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(height)	.894	.136	.877	6.592	.000
(Constant)	1.434	.496		2.889	.013

The dependent variable is ln(dbh).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.819	.670	.645	.292

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / height	-9.608	1.869	-.819	-5.140	.000
(Constant)	3.469	.184		18.810	.000

The dependent variable is ln(dbh).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.880	.775	.757	.241

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.063	.009	.880	6.683	.000
(Constant)	1.735	.144		12.043	.000

The dependent variable is ln(dbh).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.880	.775	.757	.241

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.063	.009	.880	6.683	.000
(Constant)	5.670	.817		6.940	.000

The dependent variable is ln(dbh).

Logistic

Model Summary

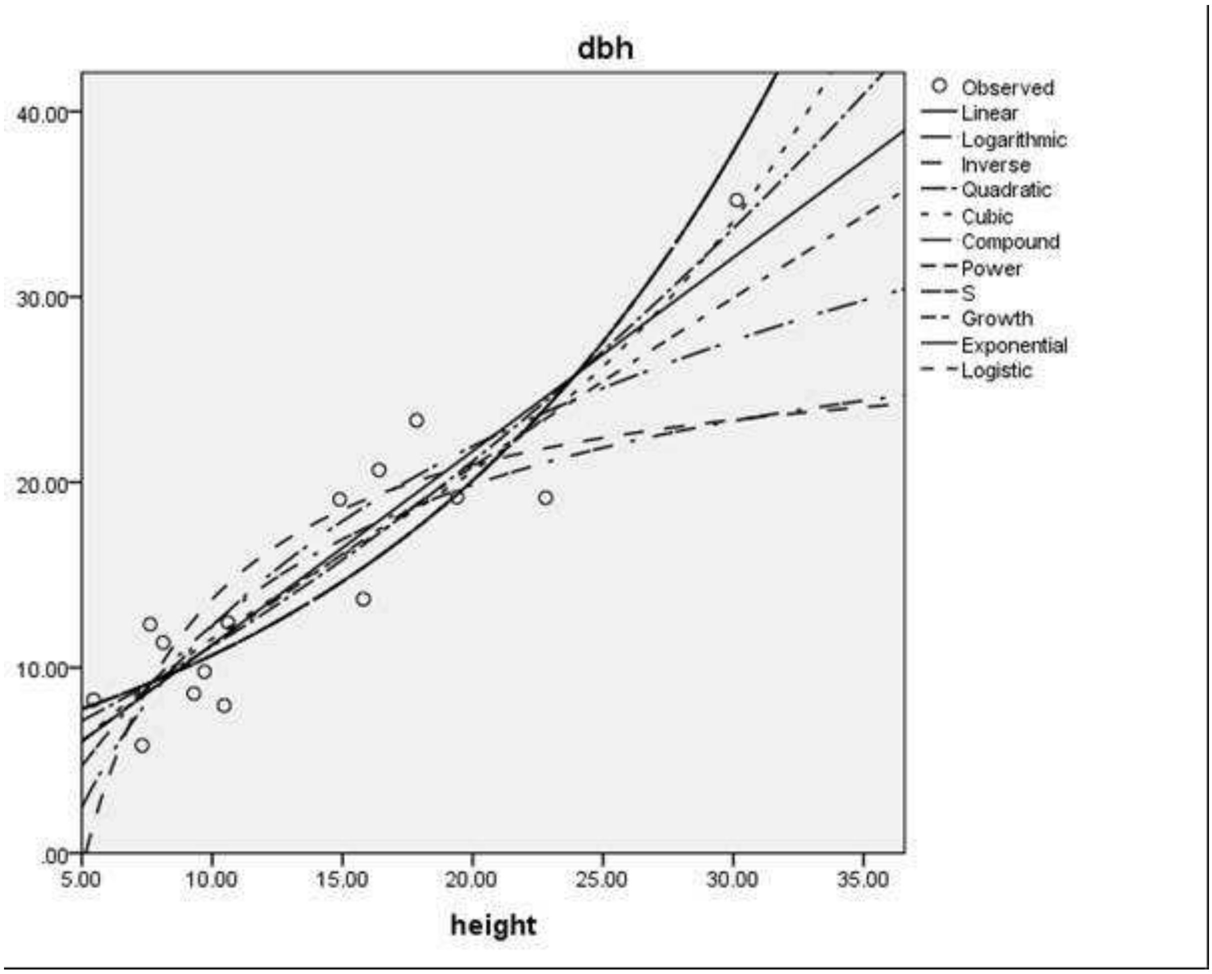
R	R Square	Adjusted R Square	Std. Error of the Estimate
.880	.775	.757	.241

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.939	.009	.415	105.596	.000
(Constant)	.176	.025		6.940	.000

The dependent variable is ln(1 / dbh).


dbh
40.00
30.00
20.00
10.00
.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
height
Observed
Linear
Logarithmic
Inverse
Quadratic
Cubic
Compound
Power
S
Growth
Exponential
Logistic

Appendix 8.4 Curve fitting for Chiddingfold felled trees: height vs age

Gompertz

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	2.233E-6	.000	.000	.000
B	14.672	102.660	-189.108	218.451
C	-.003	.023	-.048	.042

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	13384.612	3	4461.537
Residual	1722.220	96	17.940
Uncorrected Total	15106.832	99	
Corrected Total	4650.837	98	

Dependent variable: Height
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .630.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 4.182

Exponential

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	34.800	5.686	23.514	46.086
B	17.418	5.251	6.995	27.841
C	4.106	2.102	-.066	8.277

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	13998.138	3	4666.046
Residual	1108.694	96	11.549
Uncorrected Total	15106.832	99	
Corrected Total	4650.837	98	

Dependent variable: Height
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .762.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 3.398

Richard's

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
A	21.330	1.720	17.916	24.744
B	2.812	.356	2.105	3.519
C	.130	.022	.085	.174

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	14001.710	3	4667.237
Residual	1105.122	96	11.512
Uncorrected Total	15106.832	99	
Corrected Total	4650.837	98	

Dependent variable: Height
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .762.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 3.392

Korf

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	5.133	.485	4.170	6.096
B	1.637	4204573.528	-8346010.853	8346014.127
C	-.033	83498.387	-165743.022	165742.957

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	13416.556	3	4472.185
Residual	1690.276	96	17.607
Uncorrected Total	15106.832	99	
Corrected Total	4650.837	98	

Dependent variable: Height
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .637.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 4.196

Appendix 8.5 Normality test for Chiddingfold felled trees: height at specific ages

Normality tests for height by age data:

Tests of Normality[b,c,d,e,f,g]

	Age	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Height	2.00	.274	7	.122	.822	7	.068
	3.00	.381	6	.007	.720	6	.010
	4.00	.188	6	.200*	.908	6	.425
	5.00	.295	4	.	.855	4	.242
	6.00	.240	6	.200*	.920	6	.503
	7.00	.259	6	.200*	.840	6	.130
	8.00	.267	4	.	.904	4	.450
	9.00	.260	2	.			
	10.00	.257	5	.200*	.943	5	.685
	11.00	.260	2	.			
	12.00	.269	8	.090	.864	8	.132
	14.00	.261	5	.200*	.885	5	.333
	15.00	.260	2	.			
	16.00	.199	4	.	.961	4	.787
	17.00	.260	2	.			
	18.00	.385	3	.	.750	3	.000
	21.00	.403	5	.008	.623	5	.001
	22.00	.406	4	.	.681	4	.007
	28.00	.270	9	.058	.861	9	.099

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.
b. Height is constant when Age = 1.00. It has been omitted.
c. Height is constant when Age = 13.00. It has been omitted.
d. Height is constant when Age = 19.00. It has been omitted.
e. Height is constant when Age = 20.00. It has been omitted.
f. Height is constant when Age = 23.00. It has been omitted.
g. There are no valid cases for Height when Age = 24.000. Statistics cannot be computed for this level.

Appendix 8.6 Curve fitting for Chiddingfold felled trees: dbh vs height

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.954	.910	.909	2.154

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.982	.033	.954	29.966	.000
(Constant)	-3.111	.443		-7.023	.000

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.838	.701	.698	3.919

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(height)	7.936	.549	.838	14.461	.000
(Constant)	-9.344	1.288		-7.255	.000

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.622	.387	.381	5.614

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / height	-30.099	4.012	-.622	-7.503	.000
(Constant)	12.811	.841		15.241	.000

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.965	.932	.930	1.884

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.460	.102	.447	4.510	.000
height ** 2	.020	.004	.528	5.322	.000
(Constant)	-.614	.608		-1.010	.315

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.965	.932	.930	1.889

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.639	.273	.621	2.345	.021
height ** 2	.004	.022	.108	.180	.857
height ** 3	.000	.001	.258	.708	.481
(Constant)	-1.094	.912		-1.199	.234

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.875	.765	.763	.633

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	1.178	.011	2.399	103.889	.000
(Constant)	.708	.092		7.687	.000

The dependent variable is ln(dbh).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.961	.924	.924	.359

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(height)	1.659	.050	.961	32.985	.000
(Constant)	.119	.014		8.471	.000

The dependent variable is ln(dbh).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.906	.821	.819	.553

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / height	-7.979	.395	-.906	-20.198	.000
(Constant)	2.756	.083		33.295	.000

The dependent variable is ln(dbh).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.875	.765	.763	.633

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.164	.010	.875	17.043	.000
(Constant)	-.345	.130		-2.655	.009

The dependent variable is ln(dbh).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.875	.765	.763	.633

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.164	.010	.875	17.043	.000
(Constant)	.708	.092		7.687	.000

The dependent variable is ln(dbh).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.875	.765	.763	.633

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.849	.008	.417	103.889	.000
(Constant)	1.413	.184		7.687	.000

The dependent variable is ln(1 / dbh).

Appendix 8.7 Normality tests for tree volume and tree MAI by age.

Tests of Normality

	Age	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Treevol	1.00	.270	9	.058	.722	9	.003
	2.00	.199	9	.200*	.906	9	.287
	3.00	.273	9	.053	.845	9	.066
	4.00	.263	9	.074	.844	9	.064
	5.00	.236	9	.160	.867	9	.114
	6.00	.228	9	.195	.864	9	.105
	7.00	.240	9	.144	.871	9	.126
	8.00	.280	9	.041	.853	9	.080
	9.00	.288	9	.030	.829	9	.043
	10.00	.283	9	.036	.817	9	.031
	11.00	.281	9	.038	.824	9	.039
	12.00	.232	9	.177	.852	9	.079
	13.00	.194	9	.200*	.871	9	.126
	14.00	.176	9	.200*	.892	9	.207
	15.00	.169	9	.200*	.904	9	.277
	16.00	.171	9	.200*	.902	9	.262
	17.00	.171	9	.200*	.899	9	.246
	18.00	.177	9	.200*	.890	9	.202
	19.00	.176	9	.200*	.880	9	.155
	20.00	.177	9	.200*	.868	9	.117
	21.00	.183	9	.200*	.858	9	.091
	22.00	.189	9	.200*	.847	9	.069
	23.00	.196	9	.200*	.833	9	.048
	24.00	.204	9	.200*	.814	9	.030
	25.00	.212	9	.200*	.796	9	.018
	26.00	.218	9	.200*	.782	9	.013
	27.00	.220	9	.200*	.776	9	.011
	28.00	.222	9	.200*	.769	9	.009
TreeMAI	1.00	.270	9	.058	.722	9	.003
	2.00	.199	9	.200*	.906	9	.287
	3.00	.273	9	.053	.845	9	.066
	4.00	.263	9	.074	.844	9	.064

5.00	.236	9	.160	.867	9	.114
6.00	.228	9	.195	.864	9	.105
7.00	.240	9	.144	.871	9	.126
8.00	.280	9	.041	.853	9	.080
9.00	.288	9	.030	.829	9	.043
10.00	.283	9	.036	.817	9	.031
11.00	.281	9	.038	.824	9	.039
12.00	.232	9	.177	.852	9	.079
13.00	.194	9	.200*	.871	9	.126
14.00	.176	9	.200*	.892	9	.207
15.00	.169	9	.200*	.904	9	.277
16.00	.171	9	.200*	.902	9	.262
17.00	.171	9	.200*	.899	9	.246
18.00	.177	9	.200*	.890	9	.202
19.00	.176	9	.200*	.880	9	.155
20.00	.177	9	.200*	.868	9	.117
21.00	.183	9	.200*	.858	9	.091
22.00	.189	9	.200*	.847	9	.069
23.00	.196	9	.200*	.833	9	.048
24.00	.204	9	.200*	.814	9	.030
25.00	.212	9	.200*	.796	9	.018
26.00	.218	9	.200*	.782	9	.013
27.00	.220	9	.200*	.776	9	.011
28.00	.222	9	.200*	.769	9	.009

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

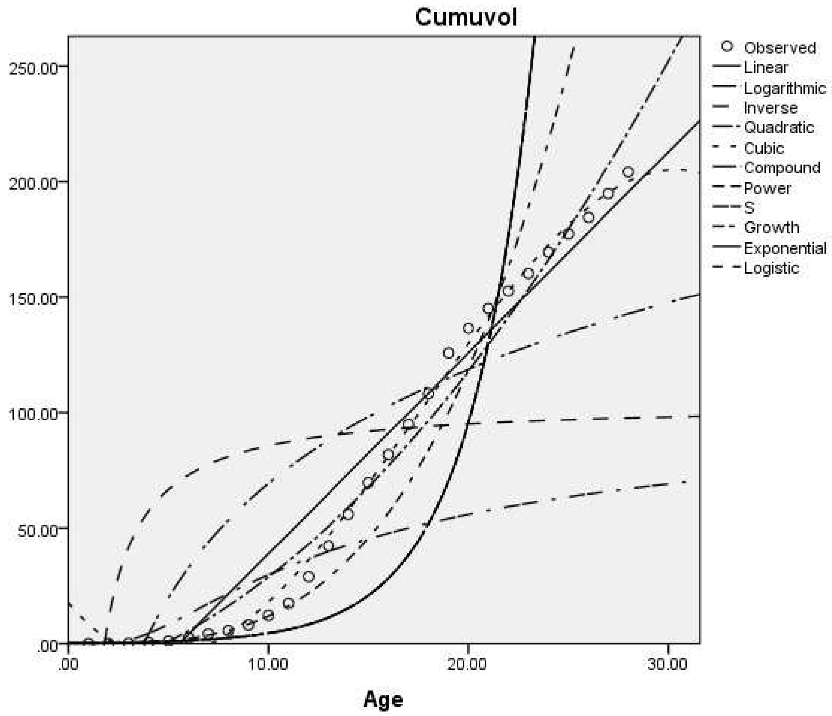
Appendix 8.8 Curve fitting for Chiddingfold felled trees: overbark volume vs age

Model Summary and Parameter Estimates

Dependent Variable: Cumuvol

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.943	433.925	1	26	.000	-48.170	8.703		
Logarithmic	.667	52.141	1	26	.000	-94.840	71.295		
Inverse	.256	8.960	1	26	.006	104.447	-188.399		
Quadratic	.976	510.365	2	25	.000	-15.628	2.195	.224	
Cubic	.996	1893.793	3	24	.000	17.690	-10.493	1.299	-.025
Compound	.795	100.813	1	26	.000	.212	1.358		
Power	.990	2493.721	1	26	.000	.006	3.322		
S	.792	99.167	1	26	.000	4.658	-12.674		
Growth	.795	100.813	1	26	.000	-1.551	.306		
Exponential	.795	100.813	1	26	.000	.212	.306		
Logistic	.795	100.813	1	26	.000	4.718	.737		

The independent variable is Age.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.971	.943	.941	17.858

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.817	.667	.654	43.324

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.506	.256	.228	64.772

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.988	.976	.974	11.843

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.998	.996	.995	5.070

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.892	.795	.787	1.301

The independent variable is Age. The dependent variable is Ln(Vol)

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.995	.990	.989	.292

The independent variable is Age. The dependent variable is Ln(Vol).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.890	.792	.784	1.310

The independent variable is Age. The dependent variable is Ln(Vol).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.892	.795	.787	1.301

The independent variable is Age. The dependent variable is Ln(Vol).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.892	.795	.787	1.301

The independent variable is Age. The dependent variable is Ln(Vol)

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.892	.795	.787	1.301

The independent variable is Age. The dependent variable is Ln(1/Vol)

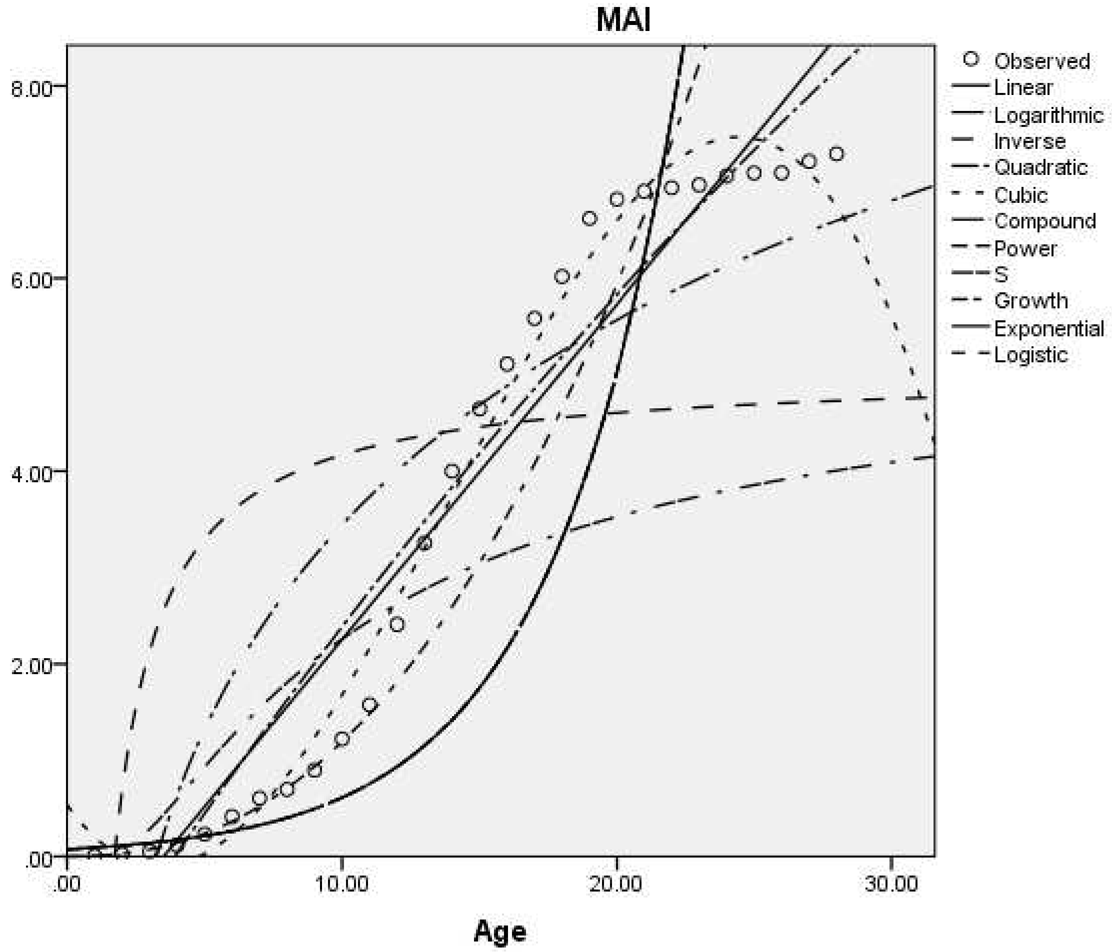
Appendix 8.9 Curve fitting for Chiddingfold felled trees: overbark MAI vs age

Model Summary and Parameter Estimates

Dependent Variable: MAI

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.934	366.416	1	26	.000	-1.221	.347		
Logarithmic	.766	84.980	1	26	.000	-3.614	3.065		
Inverse	.341	13.433	1	26	.001	5.040	-8.716		
Quadratic	.937	186.532	2	25	.000	-1.645	.432	-.003	
Cubic	.990	758.321	3	24	.000	.535	-.398	.067	-.002
Compound	.767	85.517	1	26	.000	.074	1.235		
Power	.979	1218.409	1	26	.000	.006	2.322		
S	.793	99.782	1	26	.000	1.706	-8.913		
Growth	.767	85.517	1	26	.000	-2.603	.211		
Exponential	.767	85.517	1	26	.000	.074	.211		
Logistic	.767	85.517	1	26	.000	13.505	.810		

The independent variable is Age.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.966	.934	.931	.776

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.875	.766	.757	1.459

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.584	.341	.315	2.447

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.968	.937	.932	.770

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.995	.990	.988	.321

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.876	.767	.758	.975

The independent variable is Age. The dependent variable is Ln (MAI)

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.989	.979	.978	.292

The independent variable is Age. The dependent variable is Ln (MAI)

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.891	.793	.785	.918

The independent variable is Age. The dependent variable is Ln (MAI)

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.876	.767	.758	.975

The independent variable is Age. The dependent variable is Ln (MAI)

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.876	.767	.758	.975

The independent variable is Age. The dependent variable is Ln (MAI)

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.876	.767	.758	.975

The independent variable is Age. The dependent variable is Ln (1/MAI)

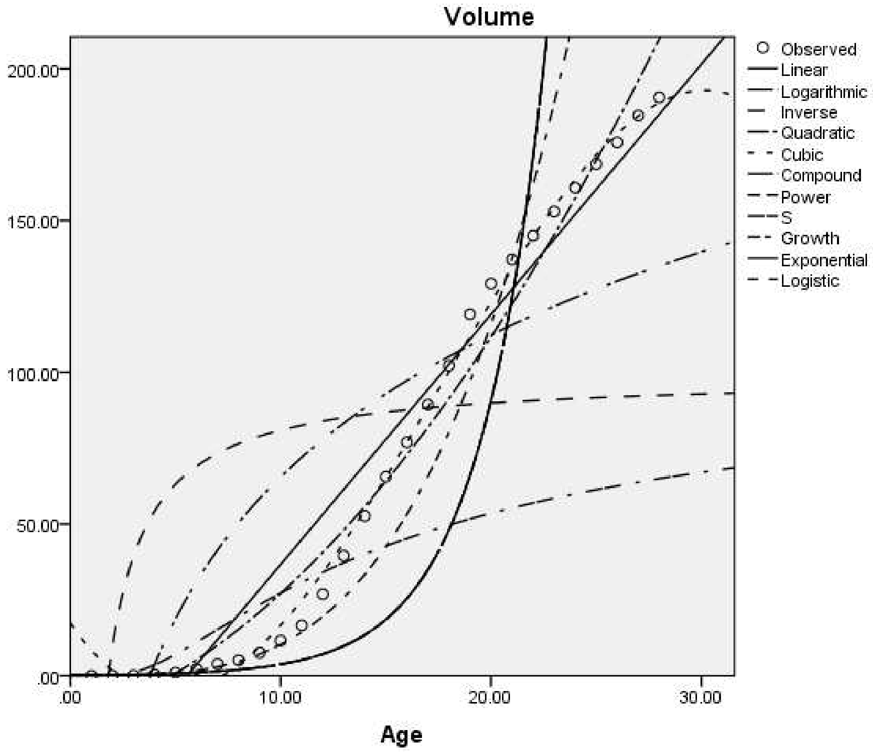
Appendix 8.10 Curve fitting for Chiddingfold felled trees: underbark volume vs age

Model Summary and Parameter Estimates

Dependent Variable: Volume

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.943	428.701	1	26	.000	-45.709	8.240		
Logarithmic	.667	51.964	1	26	.000	-89.860	67.487		
Inverse	.256	8.934	1	26	.006	98.772	-178.250		
Quadratic	.975	494.057	2	25	.000	-14.944	2.087	.212	
Cubic	.996	2019.680	3	24	.000	17.427	-10.240	1.256	-.024
Compound	.777	90.474	1	26	.000	.158	1.374		
Power	.988	2122.890	1	26	.000	.003	3.488		
S	.815	114.721	1	26	.000	4.656	-13.512		
Growth	.777	90.474	1	26	.000	-1.844	.318		
Exponential	.777	90.474	1	26	.000	.158	.318		
Logistic	.777	90.474	1	26	.000	6.320	.728		

The independent variable is Age.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.971	.943	.941	17.011

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.816	.667	.654	41.080

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.506	.256	.227	61.370

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.988	.975	.973	11.396

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.998	.996	.996	4.651

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.768	1.427

The independent variable is Age. The dependent variable is Ln(Volume)

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.994	.988	.987	.332

The independent variable is Age. The dependent variable is Ln(Volume)

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.903	.815	.808	1.298

The independent variable is Age. The dependent variable is Ln(Volume)

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.768	1.427

The independent variable is Age. The dependent variable is Ln(Volume)

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.768	1.427

The independent variable is Age. The dependent variable is Ln(Volume)

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.881	.777	.768	1.427

The independent variable is Age. The dependent variable is Ln(1/Volume)

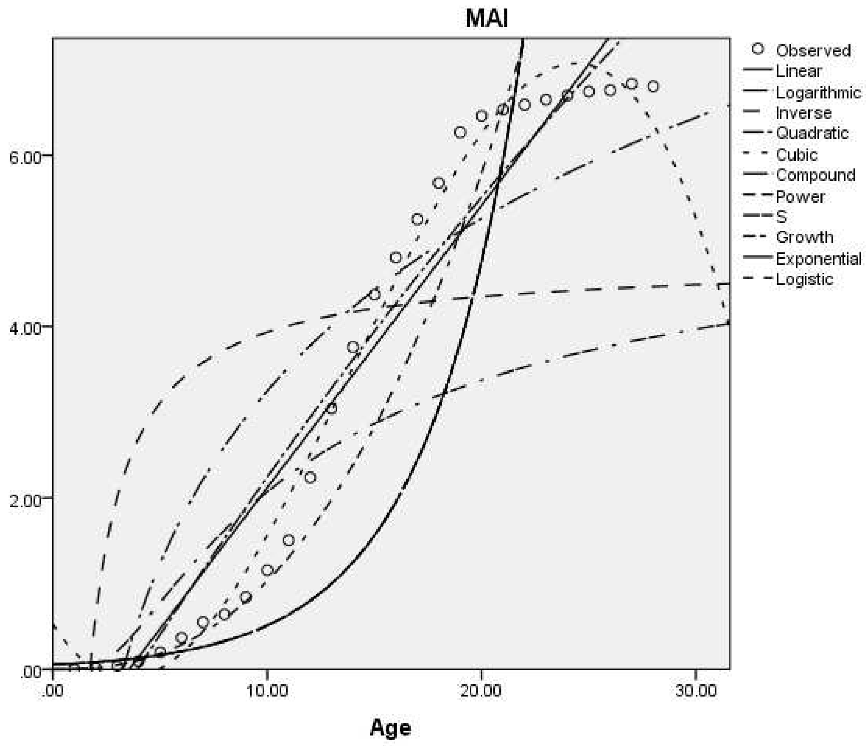
Appendix 8.11 Curve fitting for Chiddingfold felled trees: underbark MAI vs age

Model Summary and Parameter Estimates

Dependent Variable: MAI

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.934	365.260	1	26	.000	-1.173	.330		
Logarithmic	.765	84.463	1	26	.000	-3.438	2.905		
Inverse	.339	13.360	1	26	.001	4.762	-8.252		
Quadratic	.937	185.644	2	25	.000	-1.571	.409	-.003	
Cubic	.991	869.276	3	24	.000	.528	-.390	.065	-.002
Compound	.743	75.244	1	26	.000	.055	1.250		
Power	.976	1080.245	1	26	.000	.003	2.488		
S	.825	122.256	1	26	.000	1.704	-9.751		
Growth	.743	75.244	1	26	.000	-2.895	.223		
Exponential	.743	75.244	1	26	.000	.055	.223		
Logistic	.743	75.244	1	26	.000	18.089	.800		

The independent variable is Age.



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.966	.934	.931	.737

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.874	.765	.756	1.387

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.583	.339	.314	2.323

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.968	.937	.932	.732

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.995	.991	.990	.284

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.862	.743	.733	1.098

The independent variable is Age.

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.988	.976	.976	.332

The independent variable is Age.

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.908	.825	.818	.908

The independent variable is Age.

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.862	.743	.733	1.098

The independent variable is Age.

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.862	.743	.733	1.098

The independent variable is Age.

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.862	.743	.733	1.098

The independent variable is Age.

Appendix 8.12 Curve fitting for Glenbranter felled trees: height vs age

Gompertz

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	2.570E-5	.001	-.002	.003
B	12.594	45.982	-78.862	104.049
C	-.002	.008	-.019	.014

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	26885.605	3	8961.868
Residual	564.621	83	6.803
Uncorrected Total	27450.226	86	
Corrected Total	4701.509	85	

Dependent variable: Height

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .880.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 2.608

Exponential

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
A	34.297	.710	32.885	35.708
B	-2.883	2176187.593	-4328352.479	4328346.712
C	.213	160983.330	-320189.156	320189.582

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	27283.050	3	9094.350
Residual	167.176	83	2.014
Uncorrected Total	27450.226	86	
Corrected Total	4701.509	85	

Dependent variable: Height[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .964.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 1.451

Richards

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
A	37.007	.815	35.387	38.628
B	.027	8463.651	-16833.835	16833.888
C	1.101	351262.805	-698646.491	698648.693

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	27424.406	3	9141.469
Residual	25.821	83	.311
Uncorrected Total	27450.226	86	
Corrected Total	4701.509	85	

Dependent variable: Height[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .995.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 0.558

Korf

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
A	7.383	.360	6.667	8.098
B	.073	99637.782	-198175.468	198175.615
C	-.445	604854.738	-1203032.191	1203031.300

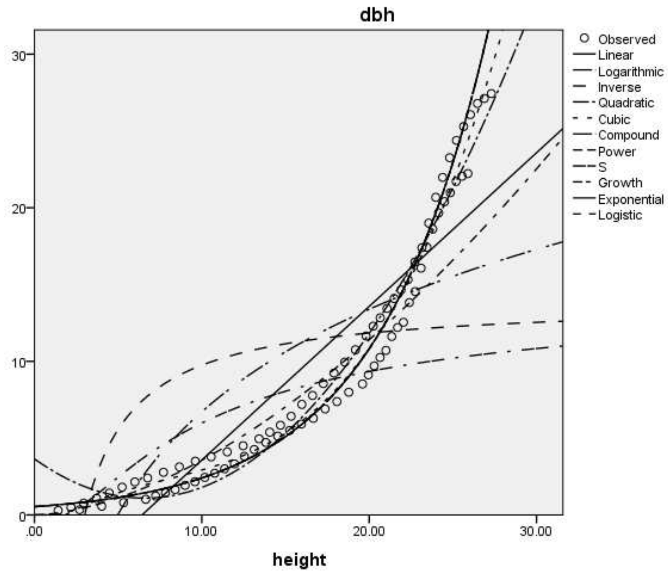
ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	26918.884	3	8972.961
Residual	531.342	83	6.402
Uncorrected Total	27450.226	86	
Corrected Total	4701.509	85	

Dependent variable: Height[a]
a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .887.

Std. Error of the Estimate (SEE) or the root mean squared error standard deviation of the error term and the square root of the Mean Square for the Residuals in the ANOVA table (see above) = 2.530

Appendix 8.13 Curve fitting for Glenbranter felled trees: dbh vs height



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.920	.846	.844	3.131

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	1.001	.047	.920	21.380	.000
(Constant)	-6.435	.841		-7.652	.000

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.783	.613	.608	4.970

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(height)	9.627	.840	.783	11.464	.000
(Constant)	-15.451	2.286		-6.760	.000

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.536	.287	.279	6.744

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / height	-41.884	7.244	-.536	-5.782	.000
(Constant)	13.935	.998		13.967	.000

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.985	.970	.969	1.389

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	-.780	.099	-.717	-7.891	.000
height ** 2	.059	.003	1.674	18.430	.000
(Constant)	3.651	.662		5.512	.000

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.992	.984	.983	1.028

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.815	.206	.750	3.963	.000
height ** 2	-.068	.016	-1.930	-4.389	.000
height ** 3	.003	.000	2.196	8.294	.000
(Constant)	-1.290	.771		-1.672	.098

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.978	.956	.955	.238

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	1.162	.004	2.658	281.199	.000
(Constant)	.534	.034		15.648	.000

The dependent variable is ln(dbh).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.965	.932	.931	.295

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(height)	1.679	.050	.965	33.676	.000
(Constant)	.075	.010		7.368	.000

The dependent variable is ln(dbh).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.805	.649	.644	.670

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / height	-8.905	.720	-.805	-12.375	.000
(Constant)	2.679	.099		27.035	.000

The dependent variable is ln(dbh).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.978	.956	.955	.238

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.150	.004	.978	42.294	.000
(Constant)	-.627	.064		-9.815	.000

The dependent variable is ln(dbh).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.978	.956	.955	.238

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.150	.004	.978	42.294	.000
(Constant)	.534	.034		15.648	.000

The dependent variable is ln(dbh).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.978	.956	.955	.238

The independent variable is height.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
height	.860	.003	.376	281.199	.000
(Constant)	1.872	.120		15.648	.000

The dependent variable is ln(1 / dbh).

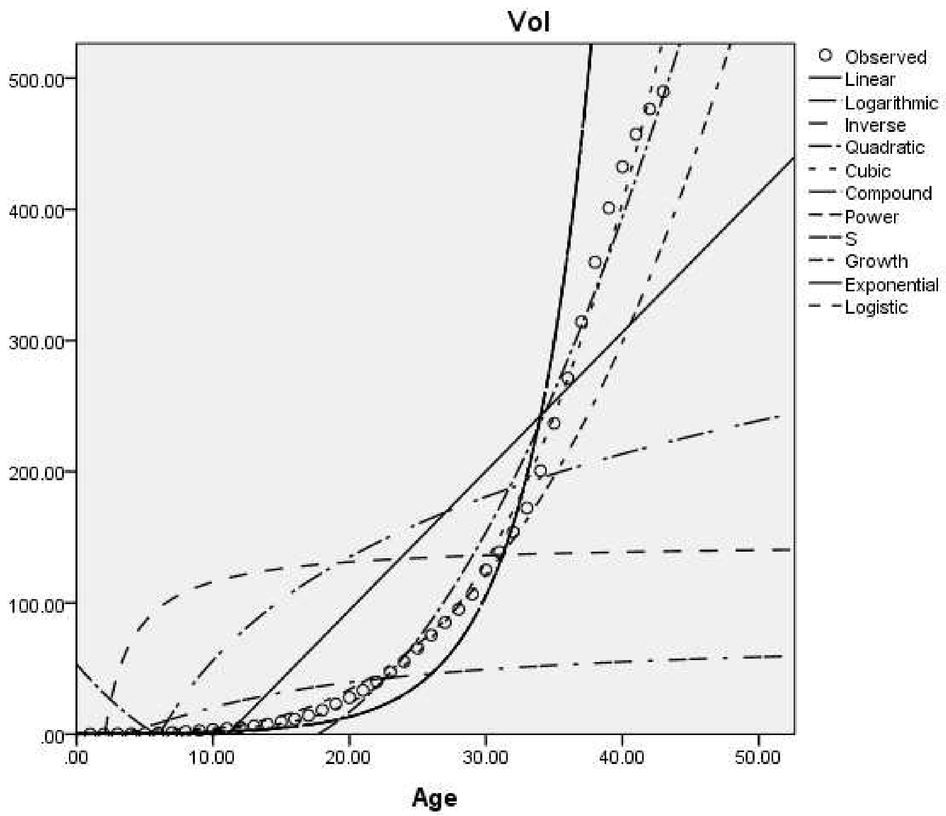
Appendix 8.14 Curve fitting for Glenbranter felled trees: overbark volume vs age.

Model Summary and Parameter Estimates

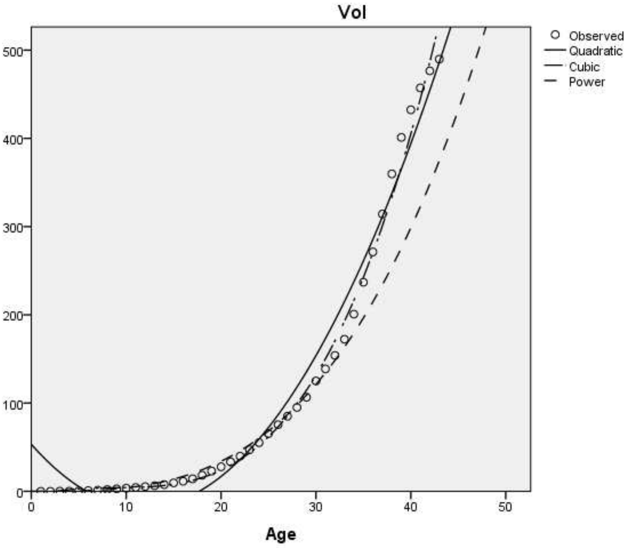
Dependent Variable: Vol

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.756	126.711	1	41	.000	-117.405	10.592		
Logarithmic	.425	30.317	1	41	.000	-205.270	113.532		
Inverse	.111	5.101	1	41	.029	146.302	-303.390		
Quadratic	.977	853.423	2	40	.000	53.263	-12.164	.517	
Cubic	.994	2094.777	3	39	.000	-6.244	3.190	-.345	.013
Compound	.891	334.401	1	41	.000	.206	1.231		
Power	.991	4378.058	1	41	.000	.003	3.135		
S	.648	75.579	1	41	.000	4.339	-13.284		
Growth	.891	334.401	1	41	.000	-1.581	.208		
Exponential	.891	334.401	1	41	.000	.206	.208		
Logistic	.891	334.401	1	41	.000	4.860	.812		

The independent variable is Age.



The three functions with the highest R^2 are compared more clearly in the graph below. The quadratic one gives negative values of volume between age of 5 and 18 years. The power one is a poorer fit at older ages of greater than 30 years. The cubic function has none of these shortcomings:



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.869	.756	.750	76.569

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.652	.425	.411	117.418

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.333	.111	.089	146.042

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.988	.977	.976	23.725

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.997	.994	.993	12.470

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.944	.891	.888	.926

The independent variable is Age. The dependent variable is Ln(Volume)

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.995	.991	.990	.270

The independent variable is Age. The dependent variable is Ln(Volume)

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.805	.648	.640	1.661

The independent variable is Age. The dependent variable is Ln(Volume)

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate

.944	.891	.888	.926

The independent variable is Age. The dependent variable is Ln(Volume)

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.944	.891	.888	.926

The independent variable is Age. The dependent variable is Ln(Volume)

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.944	.891	.888	.926

The independent variable is Age. The dependent variable is Ln(1/ Volume)

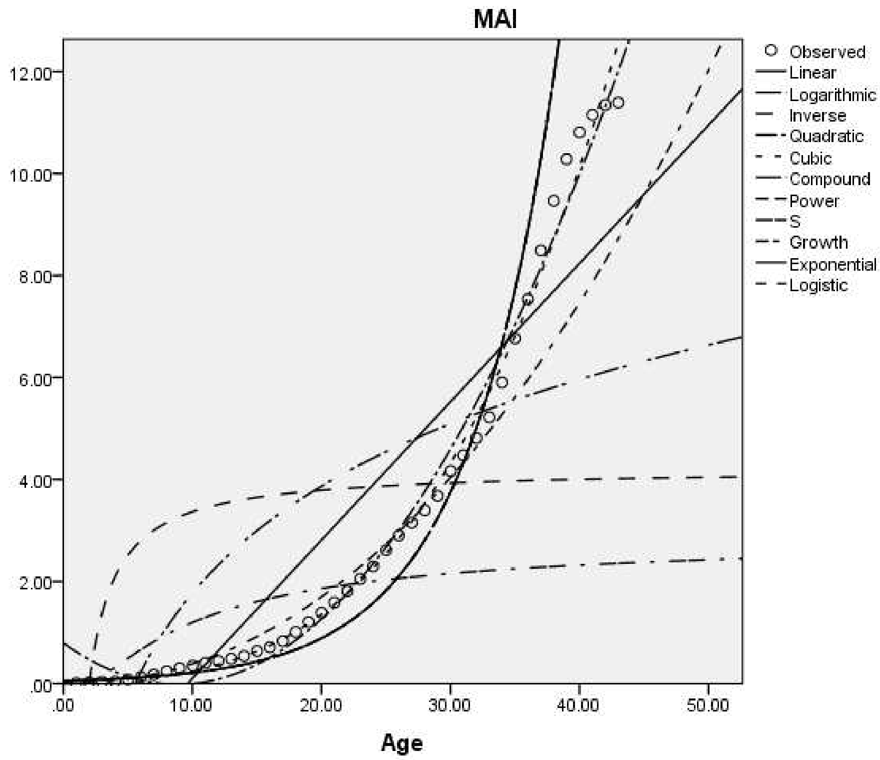
Appendix 8.15 Curve fitting for Glenbranter felled trees: MAI overbark vs age

Model Summary and Parameter Estimates

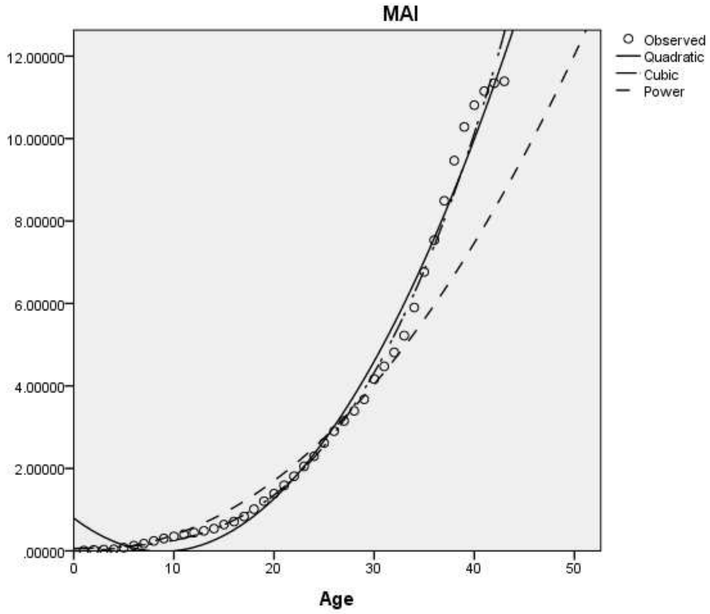
Dependent Variable: MAI

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.839	213.368	1	41	.000	-2.610	.271		
Logarithmic	.510	42.736	1	41	.000	-5.188	3.023		
Inverse	.146	7.023	1	41	.011	4.214	-8.477		
Quadratic	.988	1645.445	2	40	.000	.793	-.183	.010	
Cubic	.992	1678.050	3	39	.000	.058	.007	.000	.000
Compound	.913	430.461	1	41	.000	.050	1.155		
Power	.980	2030.504	1	41	.000	.003	2.135		
S	.613	64.850	1	41	.000	1.064	-8.841		
Growth	.913	430.461	1	41	.000	-3.003	.144		
Exponential	.913	430.461	1	41	.000	.050	.144		
Logistic	.913	430.461	1	41	.000	20.148	.866		

The independent variable is Age.



The three functions with the highest R^2 are compared more clearly in the graph below. The quadratic one gives negative values of volume between age of 5 and 10 years. The power one is a poorer fit at older ages of greater than 30 years. The cubic function has neithe of these shortcomings:



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.916	.839	.835	1.511

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.714	.510	.498	2.633

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.382	.146	.125	3.477

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.994	.988	.987	.418

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.996	.992	.992	.338

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.956	.913	.911	.566

The independent variable is Age.

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.990	.980	.980	.270

The independent variable is Age.

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.783	.613	.603	1.194

The independent variable is Age.

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.956	.913	.911	.566

The independent variable is Age.

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.956	.913	.911	.566

The independent variable is Age. The dependent variable is ln(MAI).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.948	.898	.896	.958

The independent variable is Age. The dependent variable is ln(1 / MAI - 1 / 11.400).

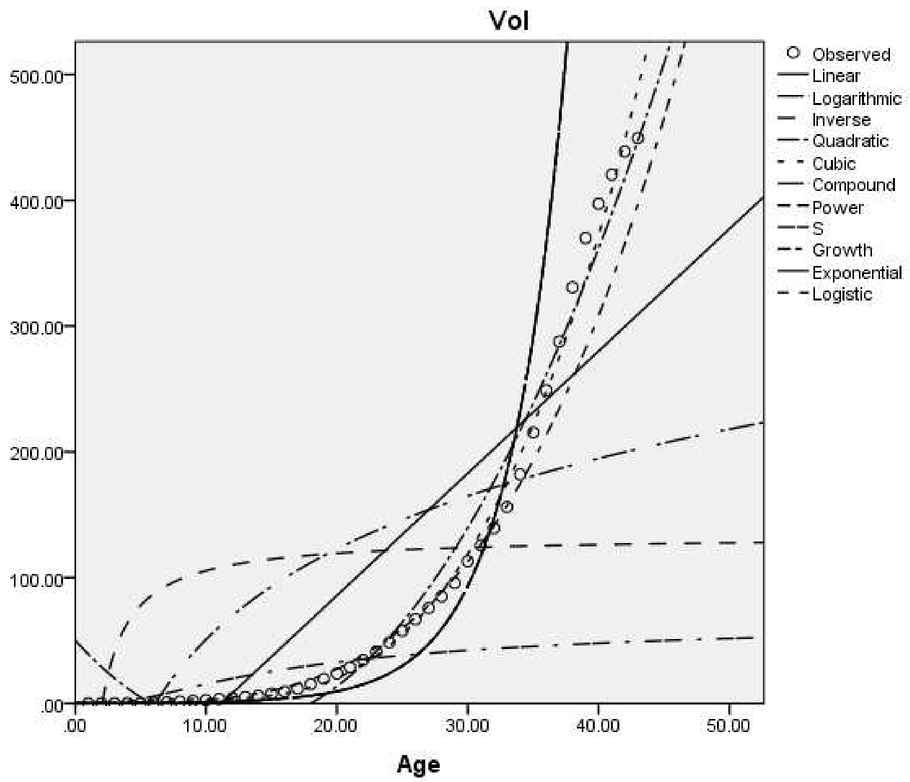
Appendix 8.16 Curve fitting for Glenbranter felled trees: underbark volume vs age

Model Summary and Parameter Estimates

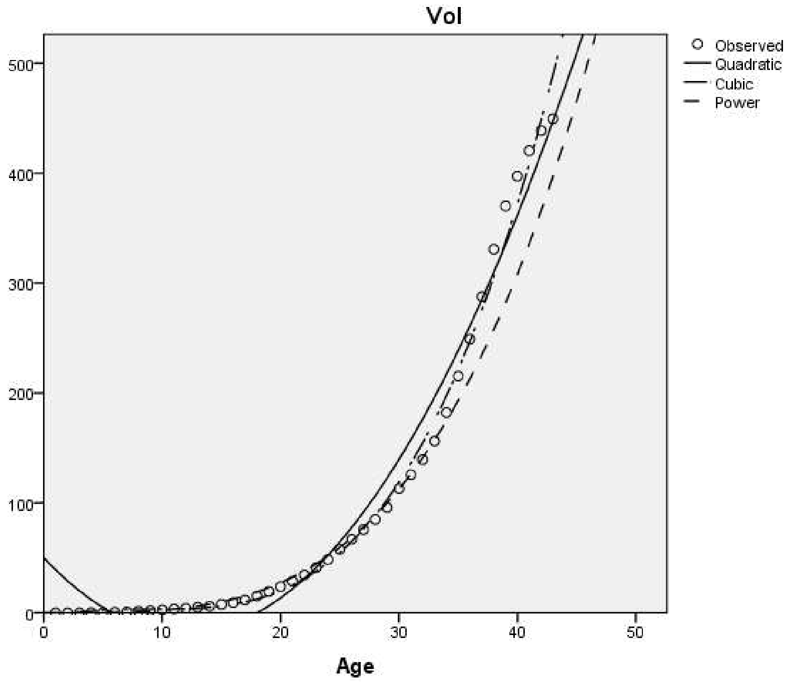
Dependent Variable: Vol

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.750	123.069	1	41	.000	-108.702	9.721		
Logarithmic	.420	29.669	1	41	.000	-188.566	103.921		
Inverse	.109	4.990	1	41	.031	133.145	-276.731		
Quadratic	.976	817.696	2	40	.000	50.067	-11.449	.481	
Cubic	.993	1966.048	3	39	.000	-5.678	2.934	-.327	.012
Compound	.862	256.165	1	41	.000	.101	1.256		
Power	.996	9425.668	1	41	.000	.001	3.498		
S	.680	86.999	1	41	.000	4.245	-15.138		
Growth	.862	256.165	1	41	.000	-2.297	.228		
Exponential	.862	256.165	1	41	.000	.101	.228		
Logistic	.862	256.165	1	41	.000	9.940	.796		

The independent variable is Age.



The three functions with the highest R^2 are compared more clearly in the graph below. The quadratic one gives negative values of volume between age of 5 and 18 years. The power one is a poorer fit at older ages of greater than 30 years. The cubic function has none of these shortcomings:



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.866	.750	.744	71.304

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.648	.420	.406	108.645

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.329	.109	.087	134.677

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.988	.976	.975	22.313

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.997	.993	.993	11.853

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.928	.862	.859	1.158

The independent variable is Age. The dependent variable is ln(Vol).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.998	.996	.996	.205

The independent variable is Age. The dependent variable is ln(Vol).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.824	.680	.672	1.764

The independent variable is Age. The dependent variable is ln(Vol).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.928	.862	.859	1.158

The independent variable is Age. The dependent variable is ln(Vol).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.928	.862	.859	1.158

The independent variable is Age. The dependent variable is ln(Vol).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.928	.862	.859	1.158

The independent variable is Age. The dependent variable is ln(1/Vol).

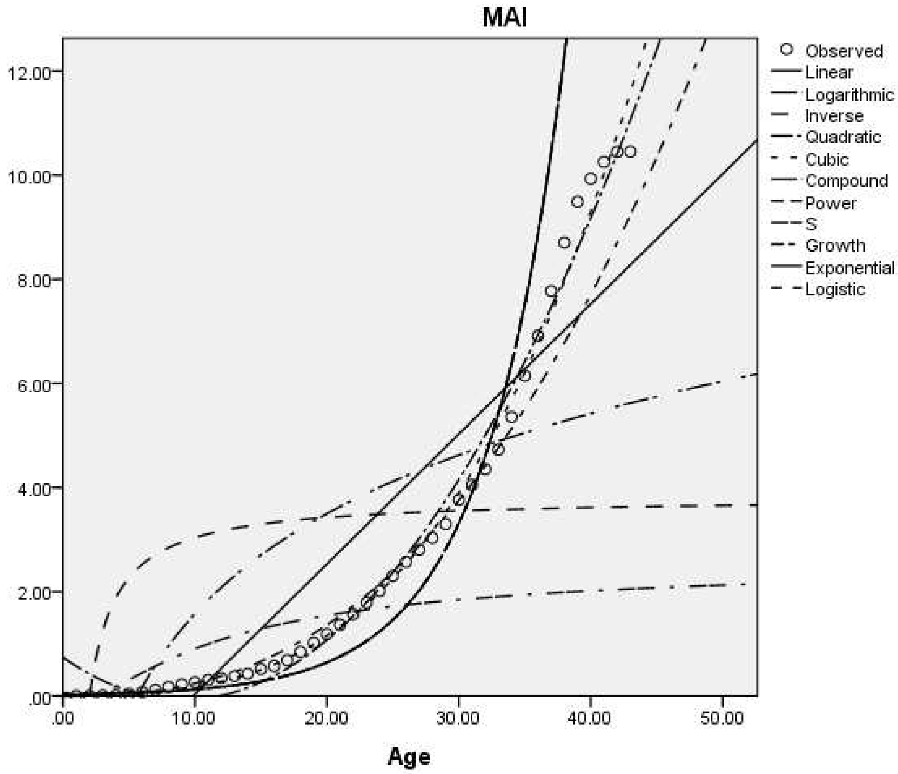
Appendix 8.17 Curve fitting for Glenbranter felled trees: underbark MAI vs age

Model Summary and Parameter Estimates

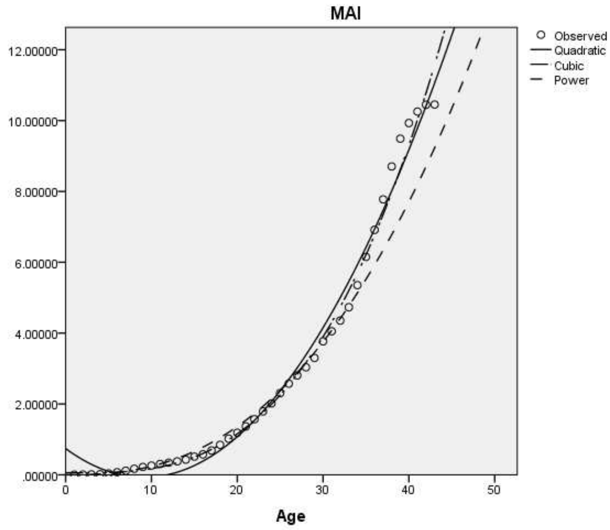
Dependent Variable: MAI

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.833	204.124	1	41	.000	-2.464	.250		
Logarithmic	.503	41.431	1	41	.000	-4.806	2.773		
Inverse	.142	6.794	1	41	.013	3.813	-7.725		
Quadratic	.988	1584.640	2	40	.000	.740	-.177	.010	
Cubic	.992	1590.612	3	39	.000	.058	-.001	.000	.000
Compound	.872	279.468	1	41	.000	.024	1.178		
Power	.992	4806.594	1	41	.000	.001	2.498		
S	.663	80.512	1	41	.000	.970	-10.695		
Growth	.872	279.468	1	41	.000	-3.719	.164		
Exponential	.872	279.468	1	41	.000	.024	.164		
Logistic	.872	279.468	1	41	.000	41.210	.849		

The independent variable is Age.



The three functions with the highest R^2 are compared more clearly in the graph below. The quadratic one gives negative values of volume between age of 5 and 12 years. The power one is a poorer fit at older ages of greater than 30 years. The cubic function has neither of these shortcomings:



Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.913	.833	.829	1.423

The independent variable is Age.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.709	.503	.490	2.453

The independent variable is Age.

Inverse

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.377	.142	.121	3.222

The independent variable is Age.

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.994	.988	.987	.393

The independent variable is Age.

Cubic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.996	.992	.991	.321

The independent variable is Age.

Compound

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.934	.872	.869	.798

The independent variable is Age. The dependent variable is ln(MAI).

Power

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.996	.992	.991	.205

The independent variable is Age. The dependent variable is ln(MAI).

S

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.814	.663	.654	1.296

The independent variable is Age. The dependent variable is ln(MAI).

Growth

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.934	.872	.869	.798

The independent variable is Age. The dependent variable is ln(MAI).

Exponential

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.934	.872	.869	.798

The independent variable is Age. The dependent variable is ln(MAI).

Logistic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.934	.872	.869	.798

The independent variable is Age. The dependent variable is ln(1/MAI).

Appendix 9 Financial analysis of SRF options

Appendix 9.1 Details of financial model for comparison of short rotation forestry species.

Yield assumptions

All species planted at 2m x 2m spacing (2,500 stems ha^{-1})

Branchwood volumes have not been included.

Coppice MAI is assumed to be 1.5 times the MAI of the first rotation. There is assumed to be no reduction in yields over coppice rotations.

E. gunnii first rotation yield is based on achieving a stem volume of 0.24 m^3 within 20 years giving a standing volume of 320 m^3 or MAI of 16 m^3 ha^{-1} y^{-1}. This assumption is based on the historic stem volume curve in Figure 5.7 which was from a site stocked at 1,350 stems ha^{-1} so is a conservative estimate of so an assumption the same volume will be made at the higher stocking in 15 years.

Coppice rotation yields are based on plots at Redmarley, Worcestershire at 10 years old which was by number of stems, $^4/_5$ *E. gunnii* and $^1/_5$ *E. dalrympleana* and achieved a MAI of 32 m^3 ha^{-1} y^{-1} (McKay 2010). Using a MAI 0f 30 m^3 ha-1 y-1 is therefore likely to be a conservative estimate of yield for a well-managed coppice stand on a productive site over a 15 year coppice cycle.

In the scenarios where *E. gunnii* has been frosted during the rotation, the yield is assumed to be: Yield at end of rotation x (age frosted/ age at end of rotation).

The only FC yield models for alder (mapped across to the sycamore yield model) were for a range of Yield Classes but only at 1.5 m spacing and intermediate thinning and so were not suitable. In alder CAI peaks at about age 20 and MAI at between 30 and 50 years (Claessens et al 2010). Volume tables from give MAI at 20 years for Hungary of between 4 and 14 m^3 $ha^{-}1$ y^{-1} and for Germany between about 3 and 7 m^3 ha^{-1} y^{-1} at ages 20 or 25 years. A MAI of 10 m^3 ha^{-1} y^{-1} has been used, as predicted by Hardcastle (2006) (calculated from the dry tonnes per ha of 5 t ha^{-1} y^{-1} and specific gravity of 0.5 given in that document) and assuming UK growth is somewhere between the growth achieved in Germany and Hungary. Coppice growth has been assumed to be 15 m^3 ha^{-1} y^{-1}.

Poplar first rotation yield was based on the FC yield model (Hamilton and Christie 1971) for black poplar hybrids on a moderately good site of YC10 and spacing of 2.7m with no thinning. At 20 years (19 years on the model) mean tree volume was 0.31 m^3 and MAI was 20.6 m^3 ha^{-1} y^{-1}. The yield used in the analysis was 20 m^3 ha^{-1} y^{-1} at 20 years of age and 30 m^3 ha-1 y-1 for coppice.

These growth rates are considerably higher than those estimated by Kerr (2011).

Financial model assumptions

Costs are based on the EWGS standard costs from 2011.

Cost of poplar sets was £0.70 each for a 1.5 m length set (The Poplar Tree Company undated).

Fencing costs are for per hectare for a 10 hectare square block (perimeter of 1,264 m).

The total establishment costs applied to all species (except poplar where cost of planting material was higher) are shown below.

Year	Activity	unit	unit cost (£)	Number units	Cost per ha
0	fencing (rabbit & deer)	metre	10	126.4	1264
0	Herbicide spray	ha	250	1	250
0	Ripping	hectare	125	1	125
0	Cost of Trees	tree	0.35	2500	875
0	Cost of planting	1000 trees	240	2.5	600
1	Spot spraying	tree	0.08	2500	200
2	Spot spraying	tree	0.08	2500	200
				Total costs	3514

When replanting costs are; costs of trees, costs of planting and the three spot sprayings (year 0,1.2).

Value per m^3 was assumed to be £13 for all but the first poplar rotation, based on recent coniferous standing sales prices (1 April 2014 – 31 March 2015) for Great Britain for tree volumes of 0.075 to 0.274 m3. Coppice material was given the same value per m^3. First rotation poplar being of a larger stem size was given a value of £18 m^3, corresponding to the value in the recent standing sales.

Scenarios

Discount rates were set at 5% for the calculation of net discounted revenue.

1. All species grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. No damaging incidents.

2. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and stems killed at 10 years but resprouted.

3. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and killed completely at 10 years requiring replanting.

4. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and stems killed at 50 years but resprouted.

5. *E. gunnii* grown for 60 years, first rotation is seedling or cutting and subsequent rotations are coppice. *E. gunnii* frosted and killed completely at 50 years requiring replanting.

Appendix 9.2 Example of financial analysis spreadsheet

Scenario 1 *Eucalyptus gunnii* - financial analysis

Timescale = 60 years

costs based on standard FC costs

			Discount rate (%)	5
15 years	MAI 1st rotation	20	NDR over 1 rotation	-1465.61
30 years	MAI 2nd rotation	30	NDR over 2 rotations	-7.93
45 years	MAI 3rd rotation	30	NDR over 3 rotations	693.24
60 years	MAI 4th rotation	30	NDR over 3 rotations	1030.51

COSTS

Year	Activity	unit	unit cost (£)	Number units	Cost per ha	discounted cost
0	fencing (rabbit & deer)	metre	10	126.4	1264	1264.00
0	Herbicide spray	ha	250	1	250	250.00
0	Ripping	hectare	125	1	125	125.00
0	Cost of Trees	tree	0.35	2500	875	875.00
0	Cost of planting	1000 trees	240	2.5	600	600.00
1	Spot spraying	tree	0.08	2500	200	190.48
2	Spot spraying	tree	0.08	2500	200	181.41
				Total costs	3514	3485.88

INCOME

-

Year	Activity	unit	unit revenue (£)	Number units	Revenue	discounted revenue
15	Harvesting	m^3	14	300	4200	2020.27
30	Harvesting	m^3	14	450	6300	1457.68
45	Harvesting	m^3	14	450	6300	701.17
60	Harvesting	m^3	14	450	6300	337.27
				Total Revenue	23100	4516.3915

Appendix 9.3 Internal Rate of Return calculations for the SRF scenarios

	E gunnii (1)	E gunnii (2)	E gunnii (3)	E gunnii (4)	E gunnii (5)	Alder	Poplar
Year	Cash flow	Cash flow	Cash flow	Cash flow	Cash flow	Cash flow	Cash flow
1	- 3,114.00	- 3,114.00	- 3,114.00	- 3,114.00	- 3,114.00	- 3,114.00	- 3,989.00
2	- 200.00	- 200.00	- 200.00	- 200.00	- 200.00	- 200.00	- 200.00
3	- 200.00	- 200.00	- 200.00	- 200.00	- 200.00	- 200.00	- 200.00
4	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-
10	-	1,866.67	- 579.00	-	-	-	-
11	-	-	- 200.00	-	-	-	-
12	-	-	- 200.00	-	-	-	-
13	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-
15	4,200.00	-	-	4,200.00	4,200.00	-	-
16	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-
20	-	-	-	-	-	2,800.00	7,200.00
21	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-
24	-	-		-	-	-	-
25	-	6,300.00	6,300.00	-	-	-	-
26	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-
30	6,300.00	-	-	6,300.00	6,300.00	-	-
31	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-
33	-	-	-	-	-	-	-
34	-	-	-	-	-	-	-
35	-	-	-	-	-	-	-
36	-	-	-	-	-	-	-
37	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-
39	-	-	-	-	-	-	-

40	-	6,300.00	6,300.00	6,300.00	6,300.00	2,800.00	8,400.00
41	-	-	-	-	-	-	-
42	-	-	-	-	-	-	-
43	-	-	-	-	-	-	-
44	-	-	-	-	-	-	-
45	6,300.00	-	-	-	-	-	-
46	-	-	-	-	-	-	-
47	-	-	-	-	-	-	-
48	-	-	-	-	-	-	-
49	-	-	-	-	-	-	-
50	-	-	-	700.00	- 1,025.00	-	-
51	-	-	-	-	- 200.00	-	-
52	-	-	-	-	- 200.00	-	-
53	-	-	-	-	-	-	-
54	-	-	-	-	-	-	-
55	-	6,300.00	6,300.00	-	-	-	-
56	-	-	-	-	-	-	-
57	-	-	-	-	-	-	-
58	-	-	-	-	-	-	-
59	-	-	-	-	-	-	-
60	6,300.00	700.00	700.00	2,800.00	2,800.00	2,800.00	8,400.00
IRR	**6.3%**	**6.2%**	**4.5%**	**6.4%**	**6.3%**	**2.5%**	**5.2%**